SWIFT AS AN UNPRECEDENTED PROBE OF YOUNG, CSM-INTERACTING SUPERNOVAE

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NHFP
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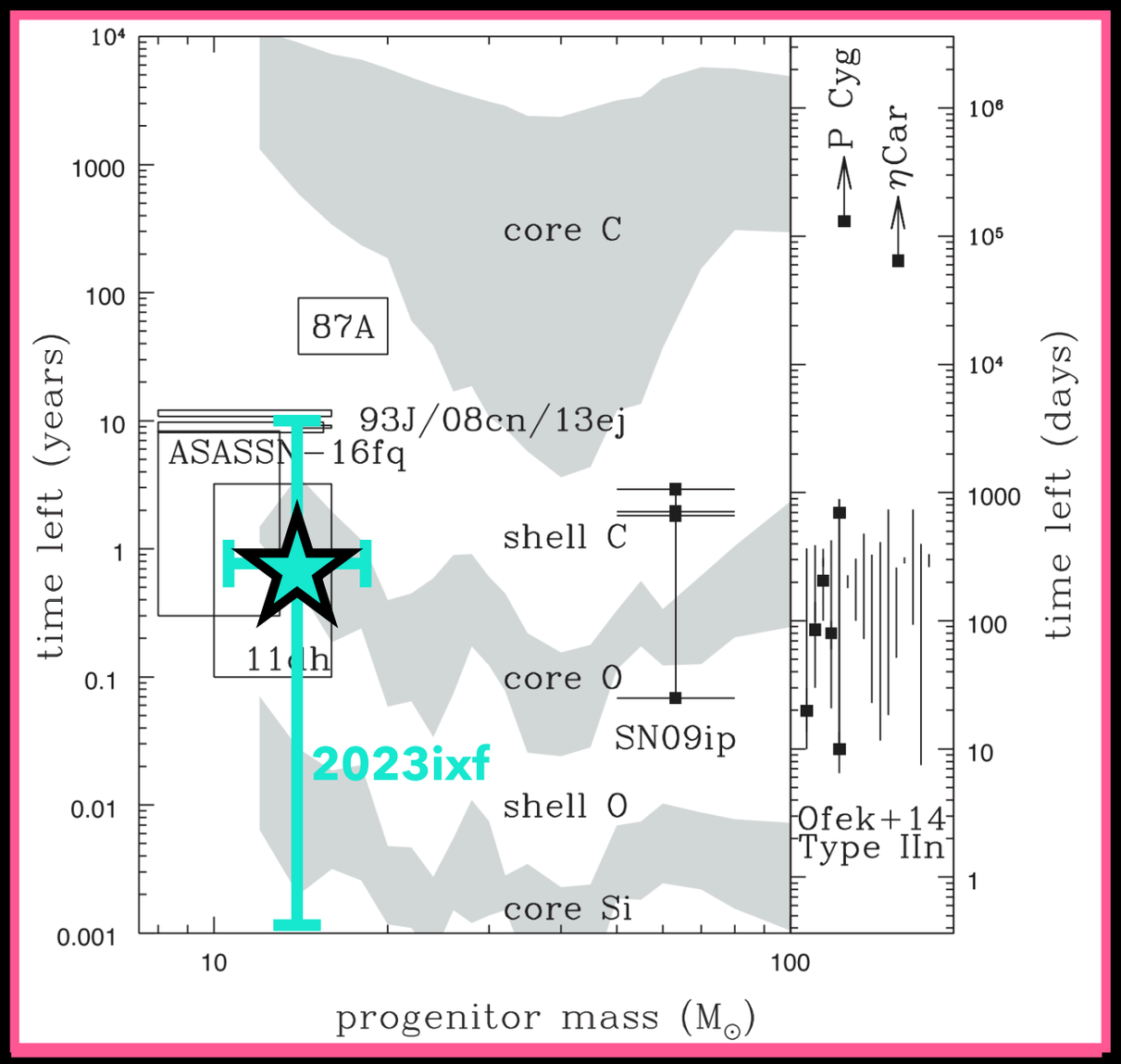
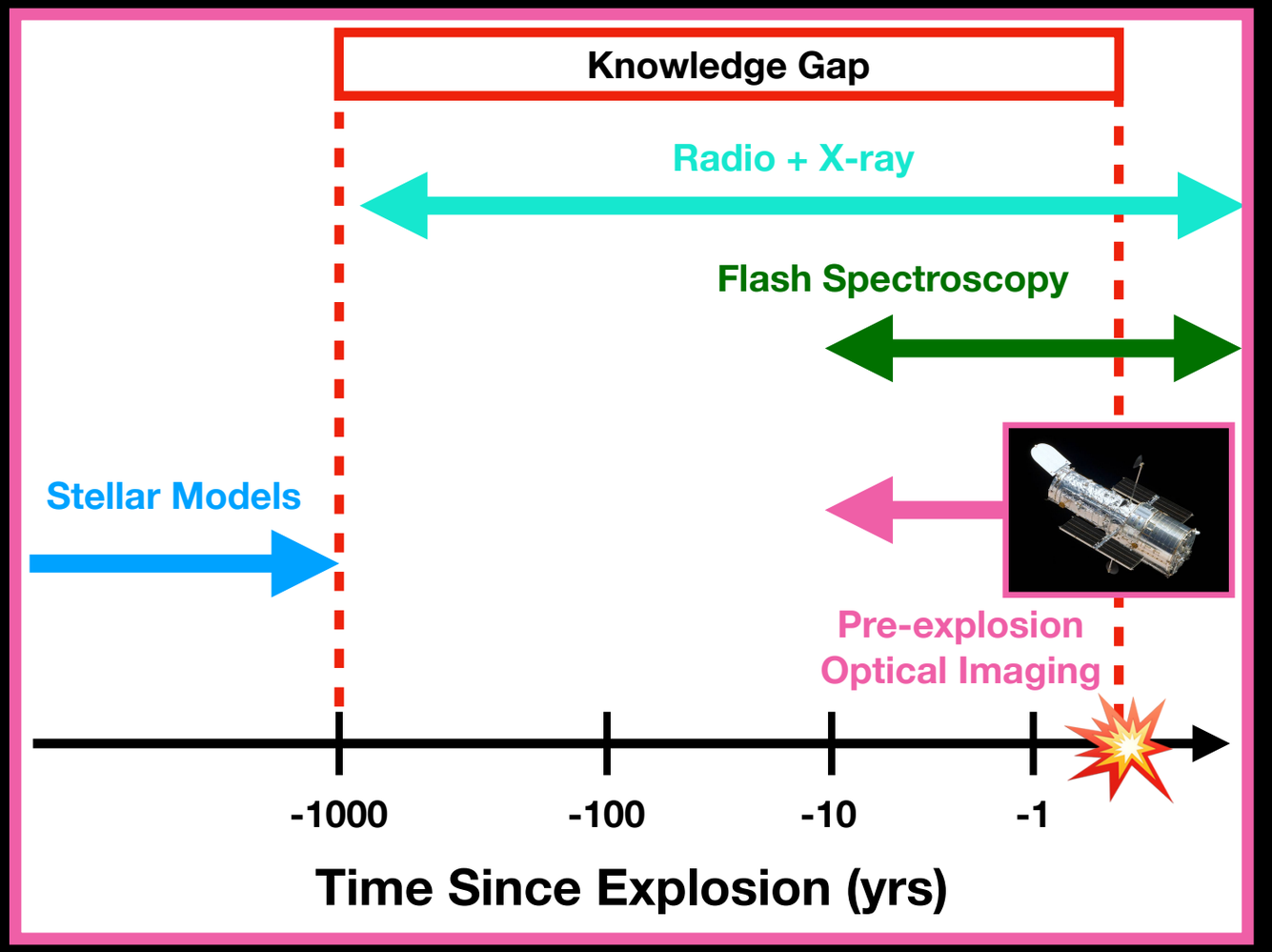
Fellowship Program

WHAT DO STARS DO BEFORE THEY DIE?

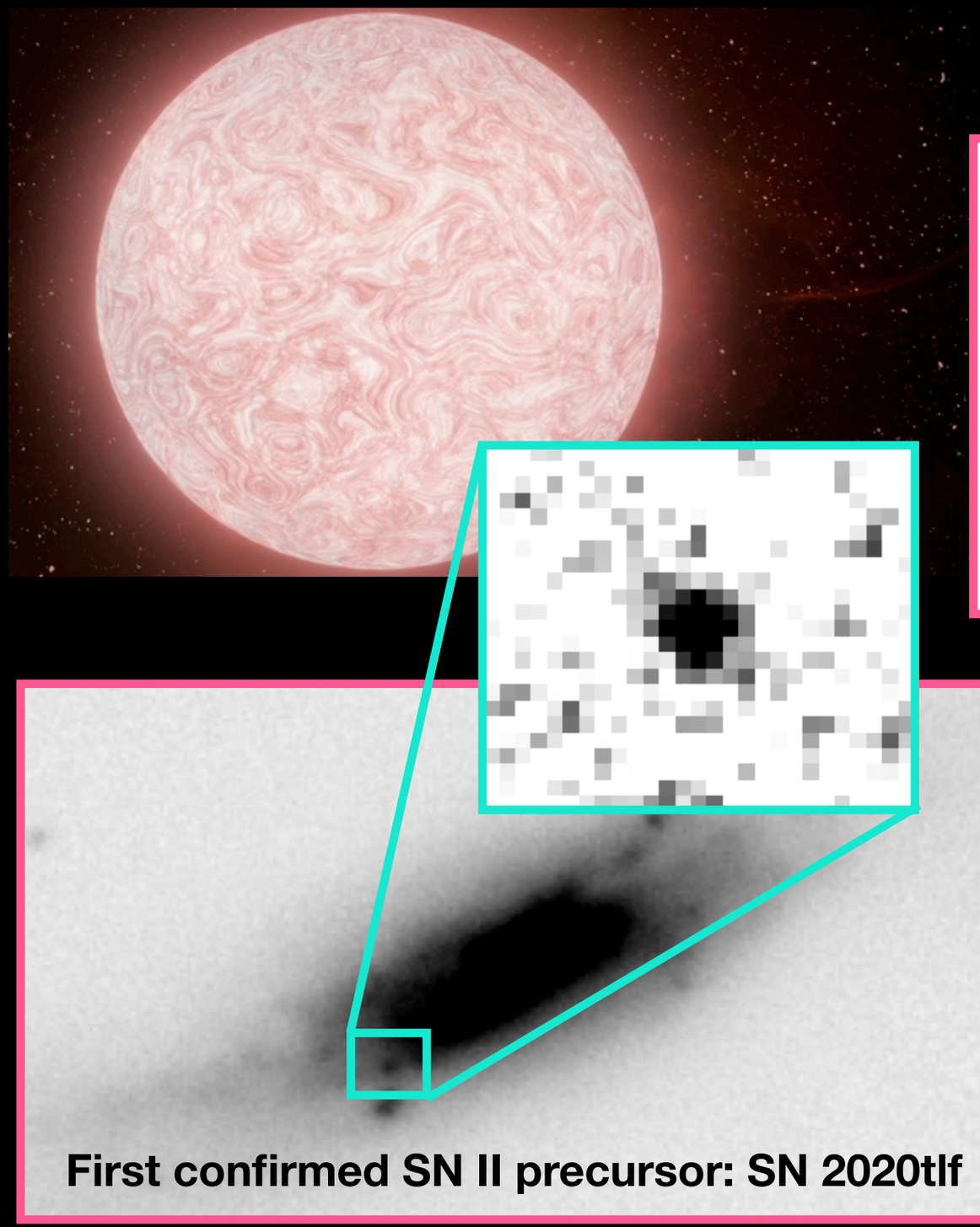


Kochanek+ 2017



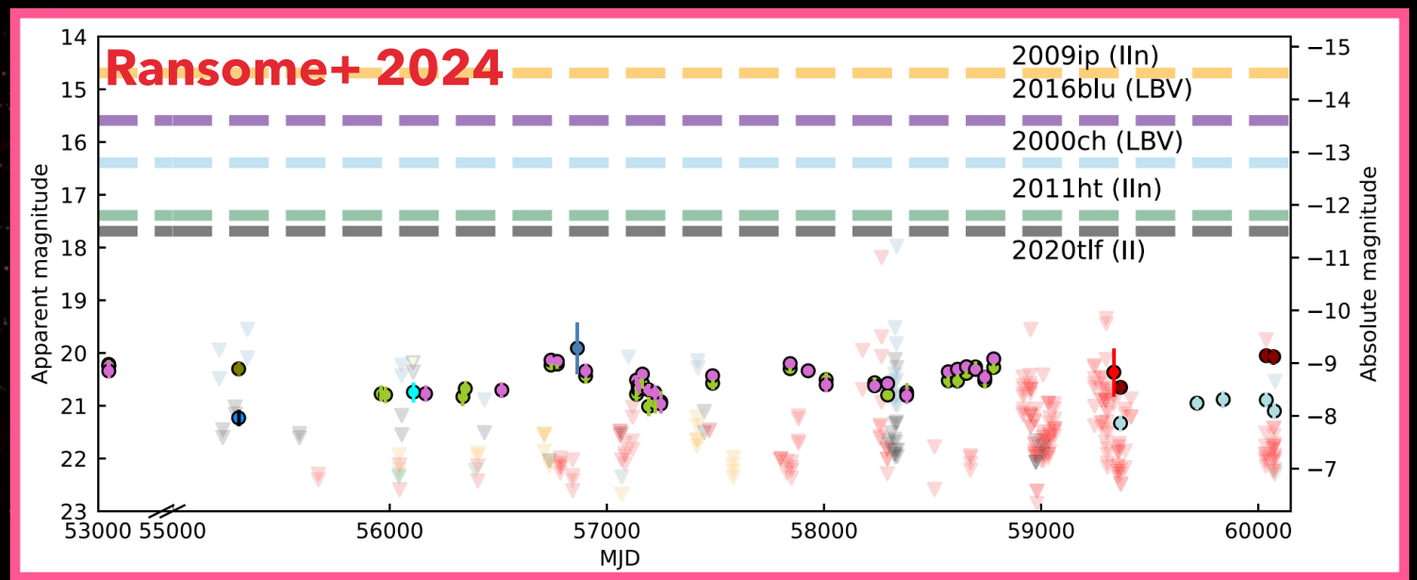
Early-time, multi-wavelength observations have led to the most significant breakthroughs in all supernova sub-types.

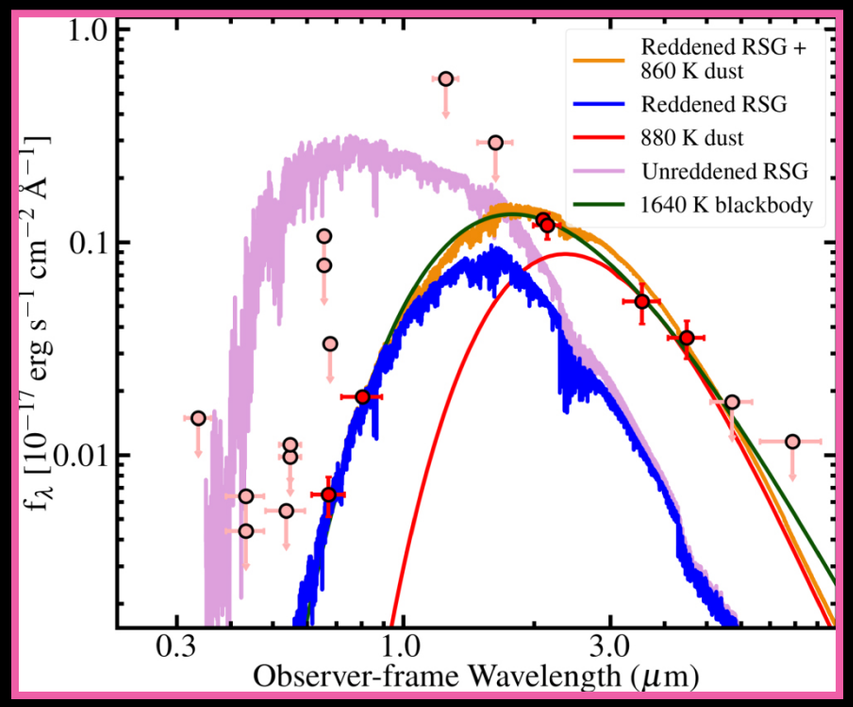
WHAT DO RED SUPERGIANTS DO IN THE YEAR(S) BEFORE THEY DIE?



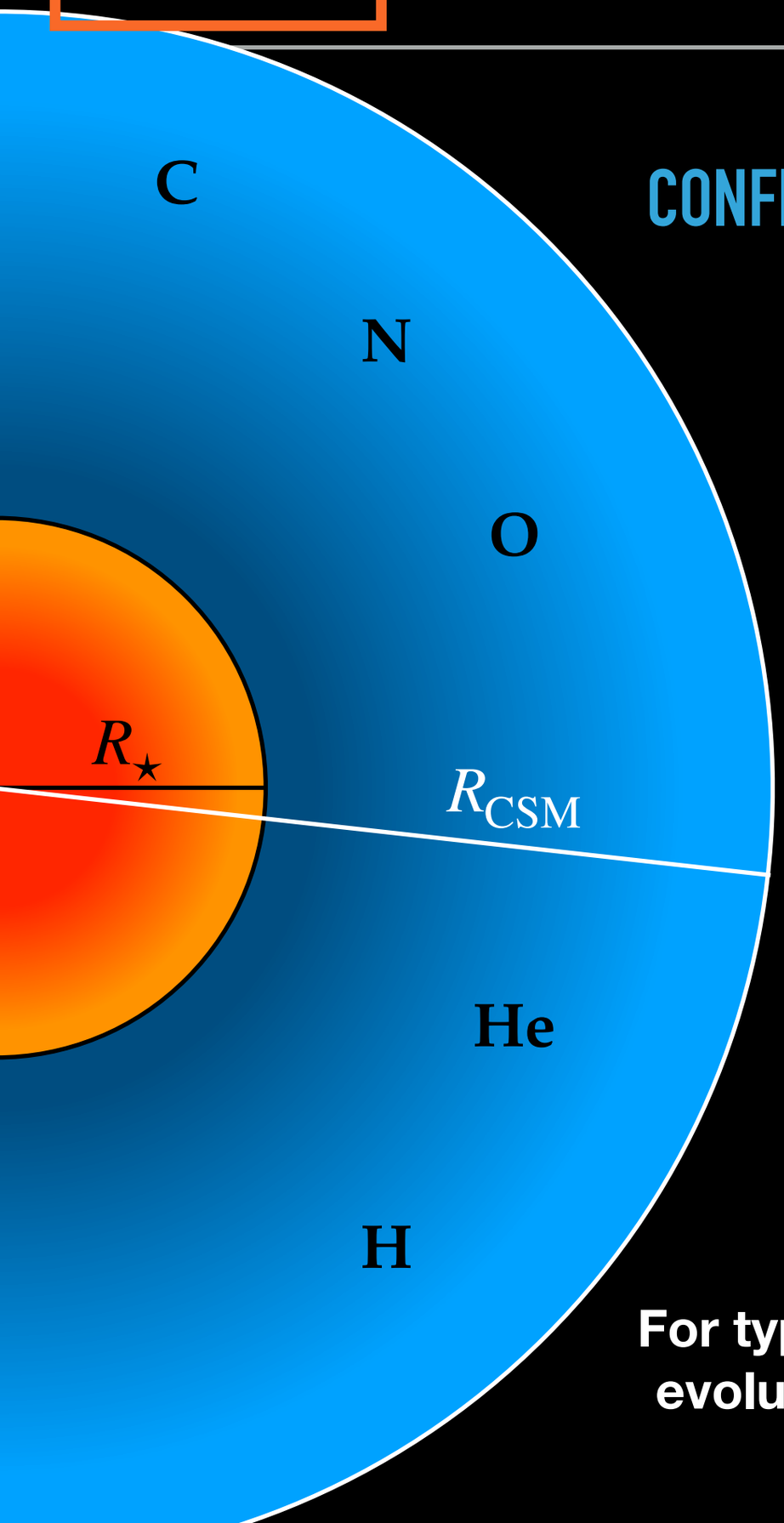
WJG+ 2022a

Tight constraints on precursor activity in very nearby events: SNe 2023ixf & 2024ggi





Kilpatrick+ 2023

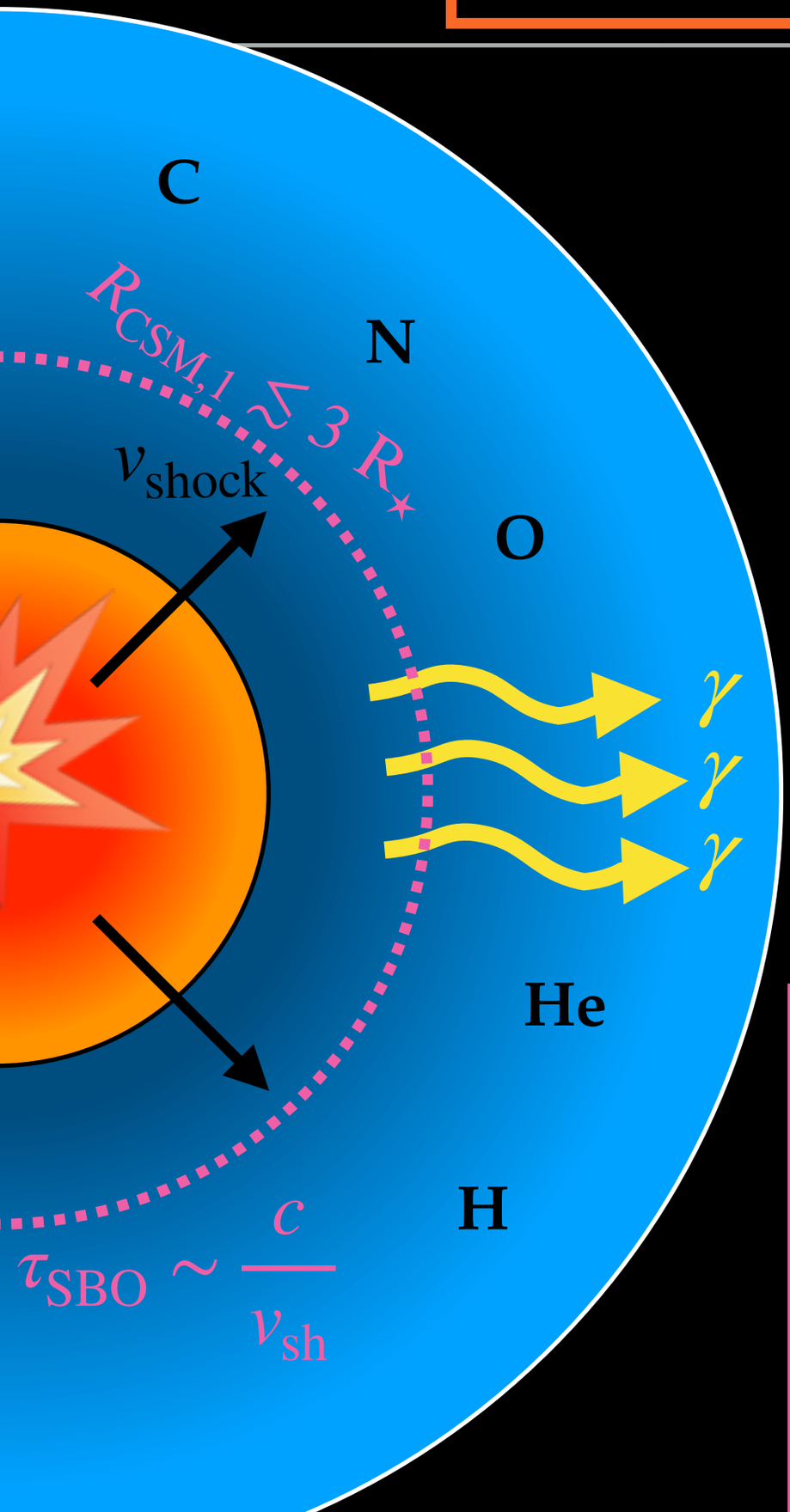


CONFINED CIRCUMSTELLAR MATERIAL IS A DIRECT PROBE OF:

1. Late-stage stellar evolution
2. Mass-loss (e.g., binary interaction, eruptive, steady-state)
3. SN progenitor identity
4. Shock physics / dynamics / breakout

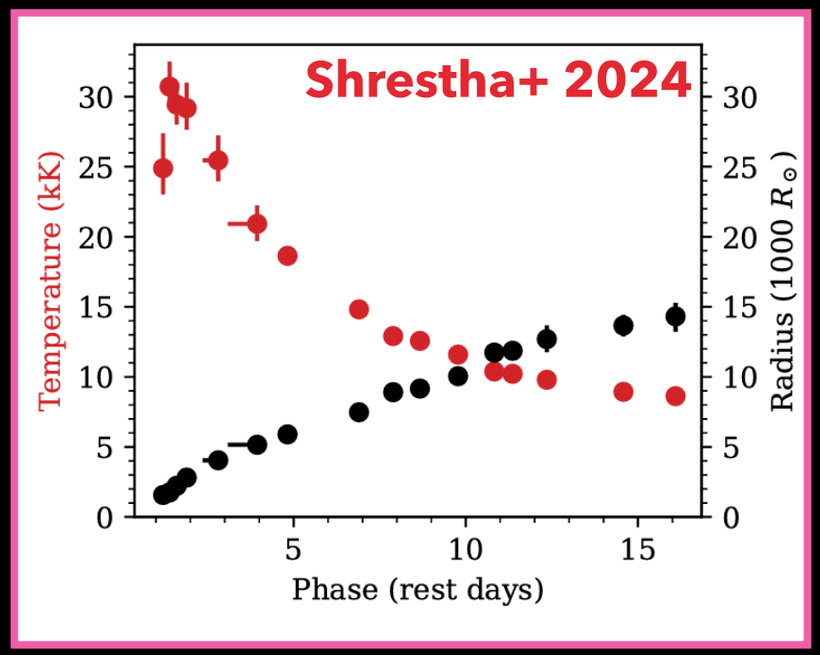
$$t_{\rm preSN} = \frac{R_{\rm Sh}}{v_w} = t_{\rm SN} \times \frac{v_{\rm Sh}}{v_w}$$

For typical RSG shock and wind velocities, the final decade of evolution needs observations of the SN during its first week.

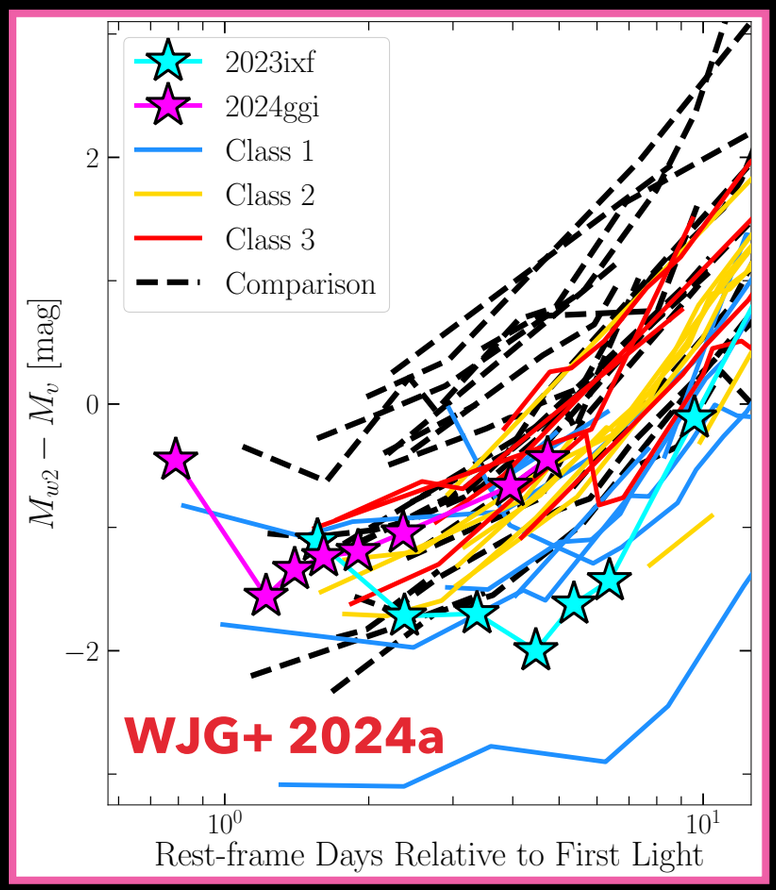


CSM SHOCK BREAKOUT

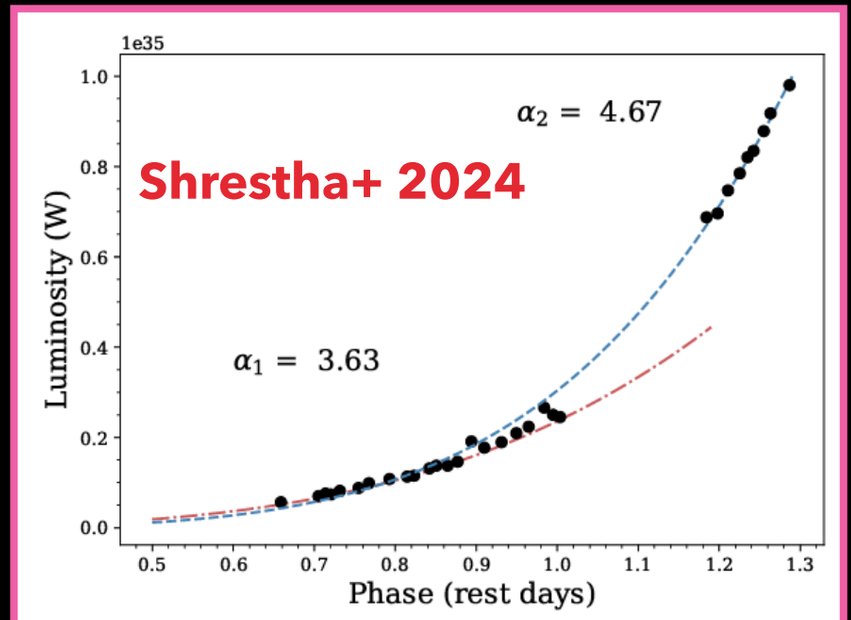
Rising temperature/ionization:



Red-to-blue color evolution:



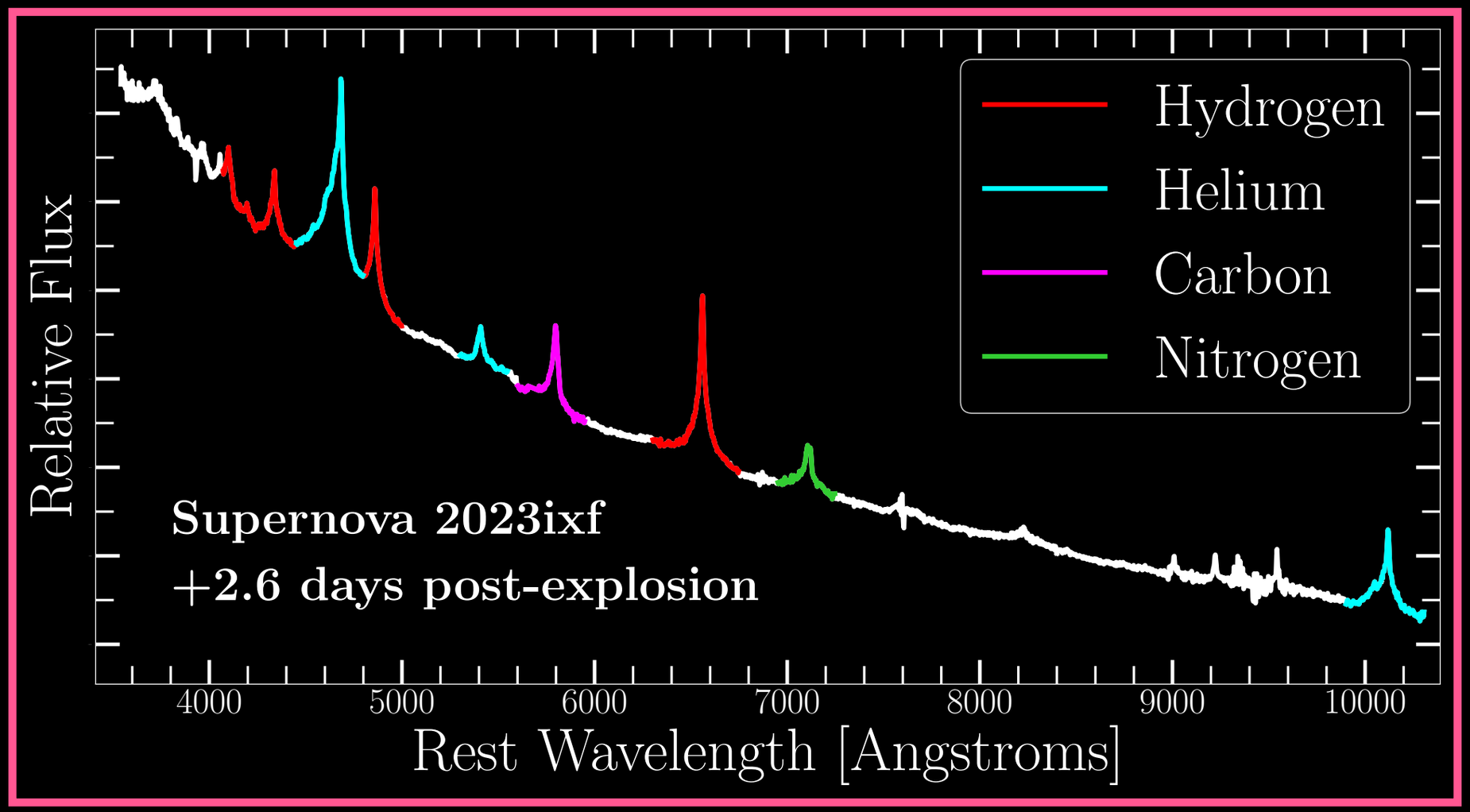
Multi-component rise:



t_{SBO}

WHAT DO RED SUPERGIANTS DO IN THE YEAR(S) BEFORE THEY DIE?

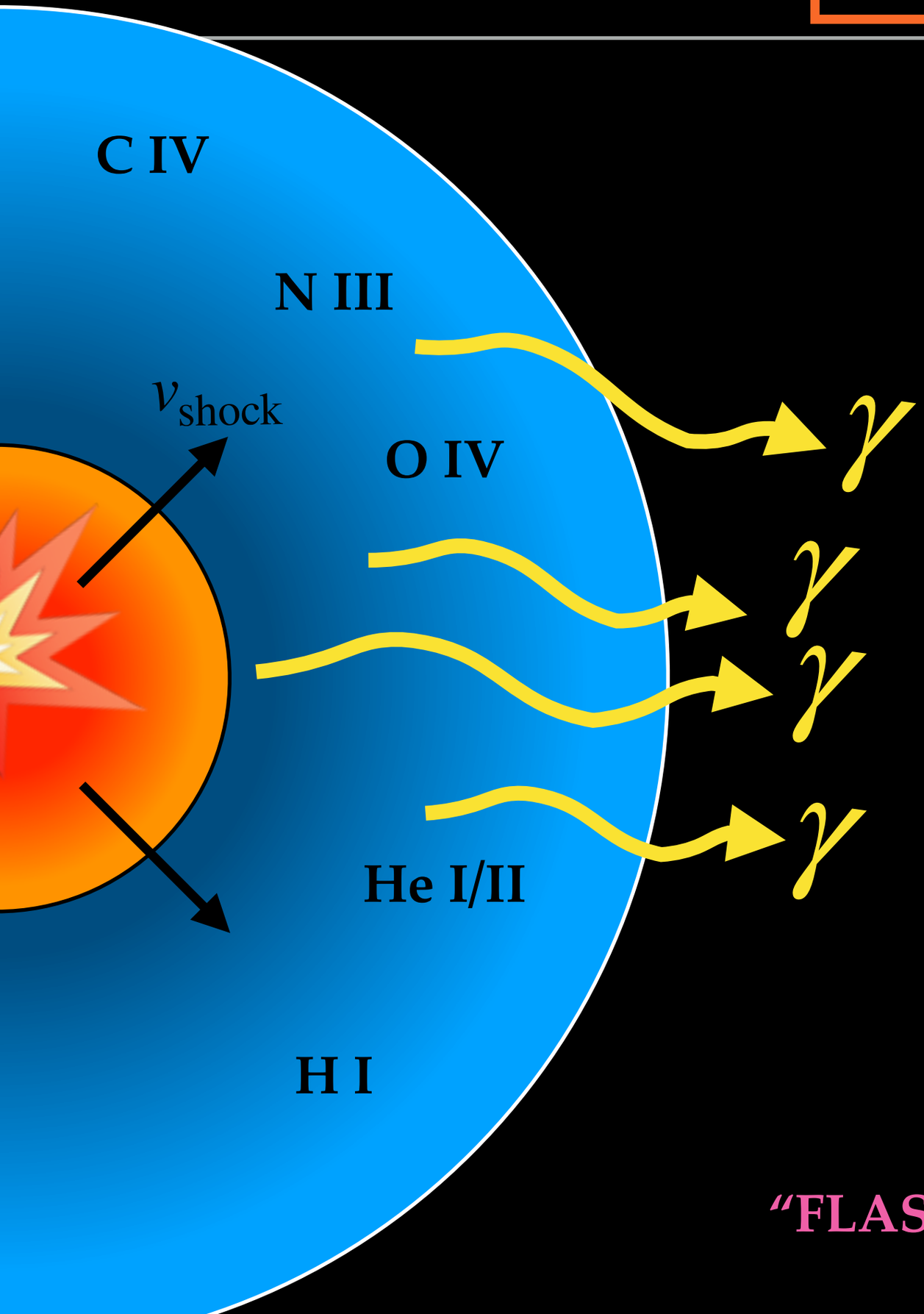
Early-time, "flash" spectroscopy of type II supernovae indicates enhanced red supergiant mass-loss



$\dot{M} \sim 10^{-3} - 10^{-2}\ \mathrm{M_\odot yr^{-1}}$

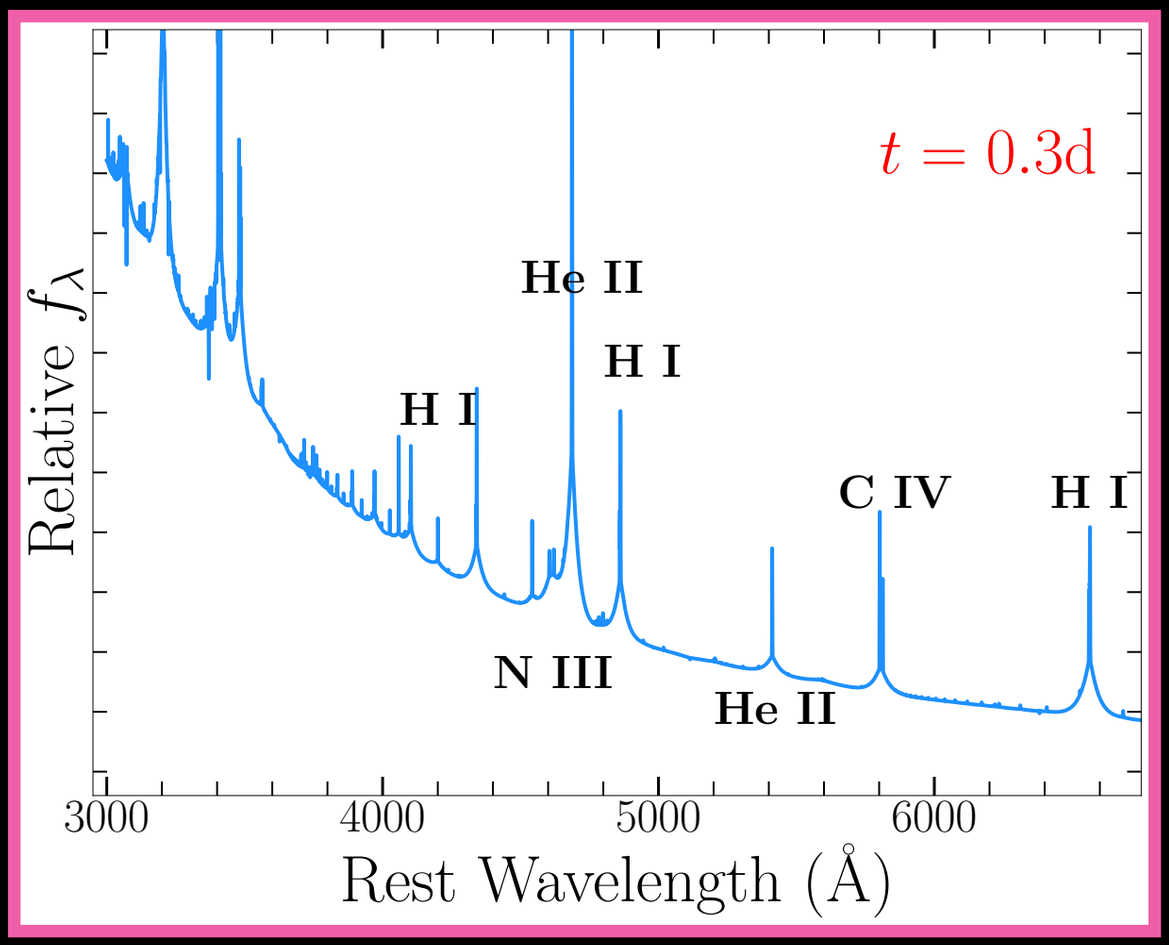
$R_{\mathrm{CSM}} \sim 10^{15}$ cm

WJG+ 2023



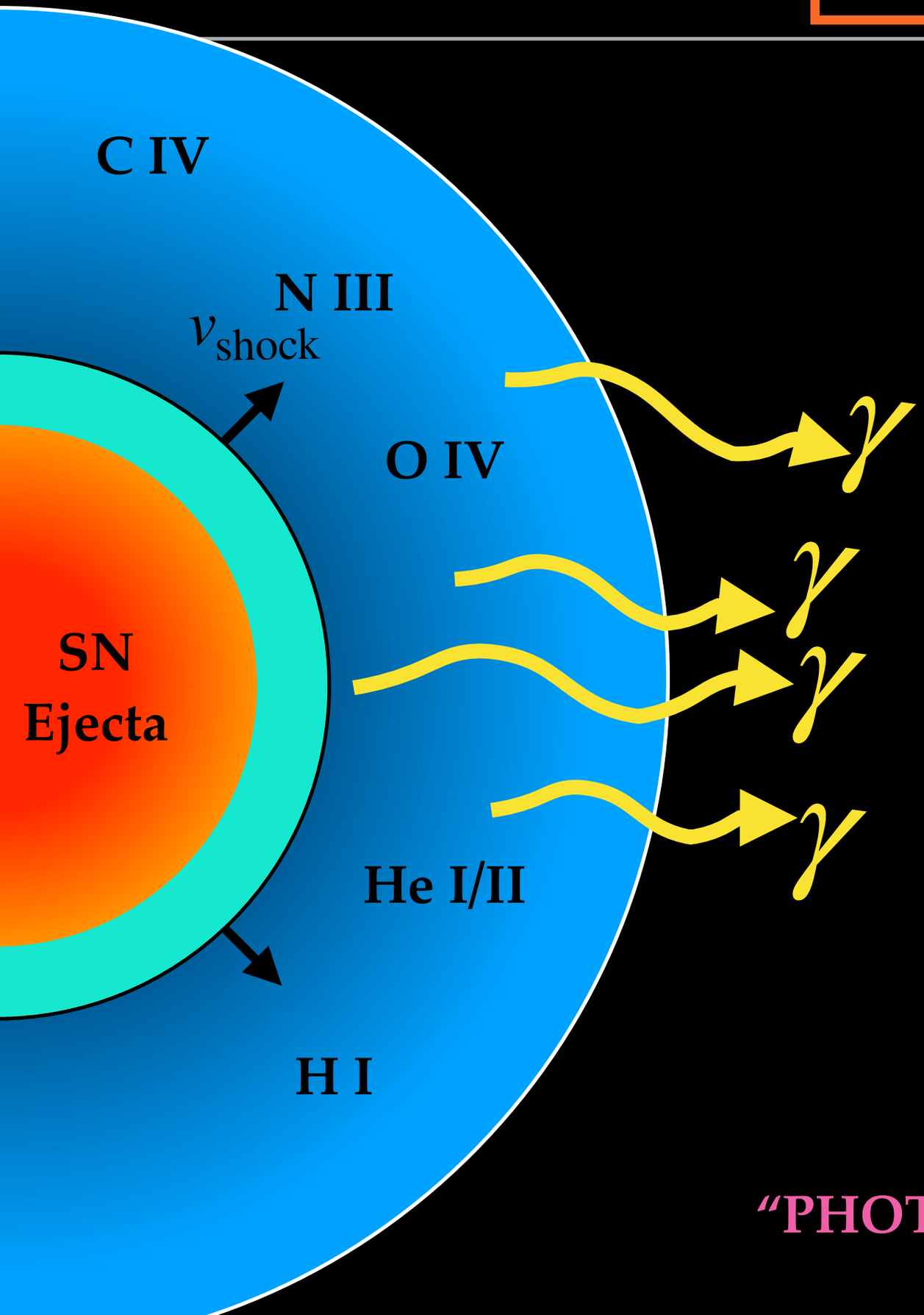
EXAMPLE CASE:

$\dot{M} = 10^{-2}\ \mathrm{M_\odot yr^{-1}}, r \approx 10^{15}$ cm



"FLASH IONIZATION"

$t_{\rm flash}$



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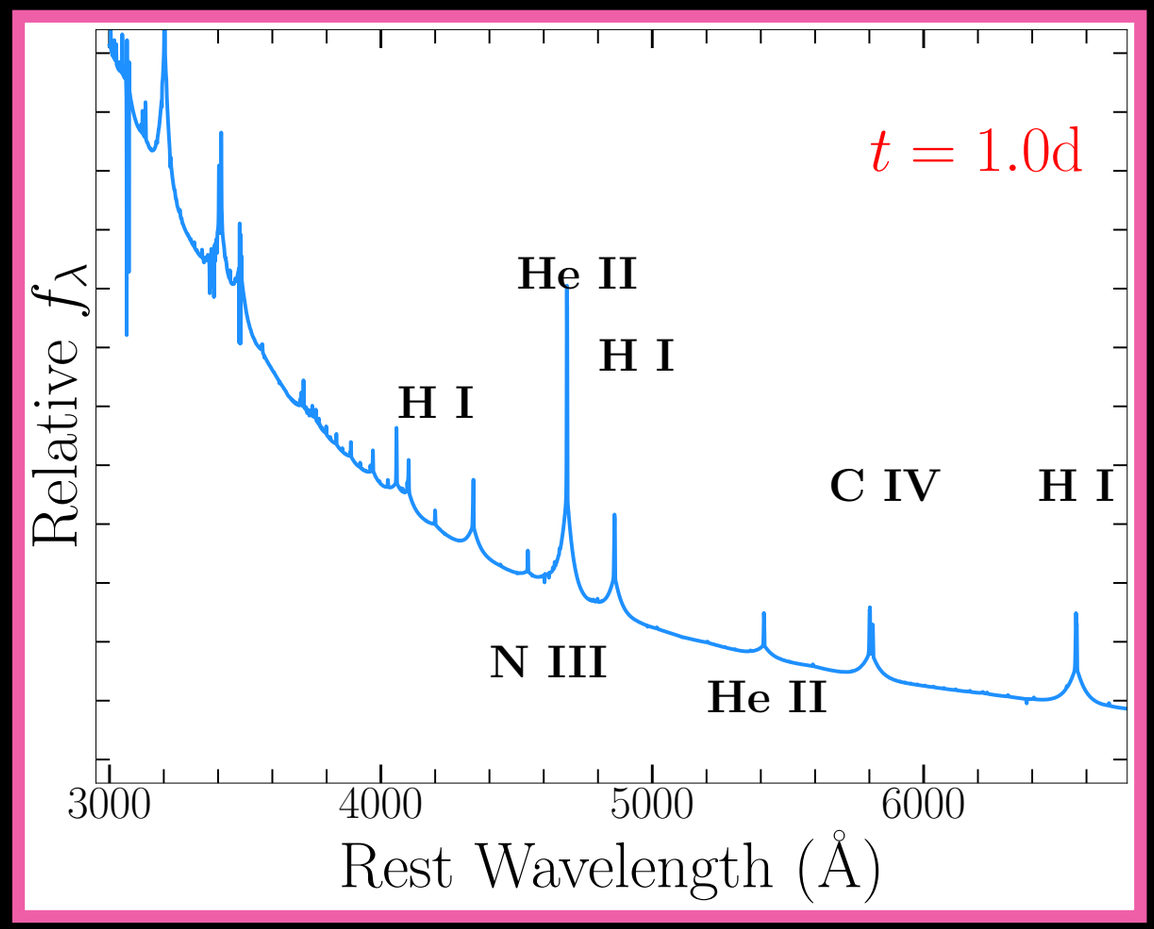
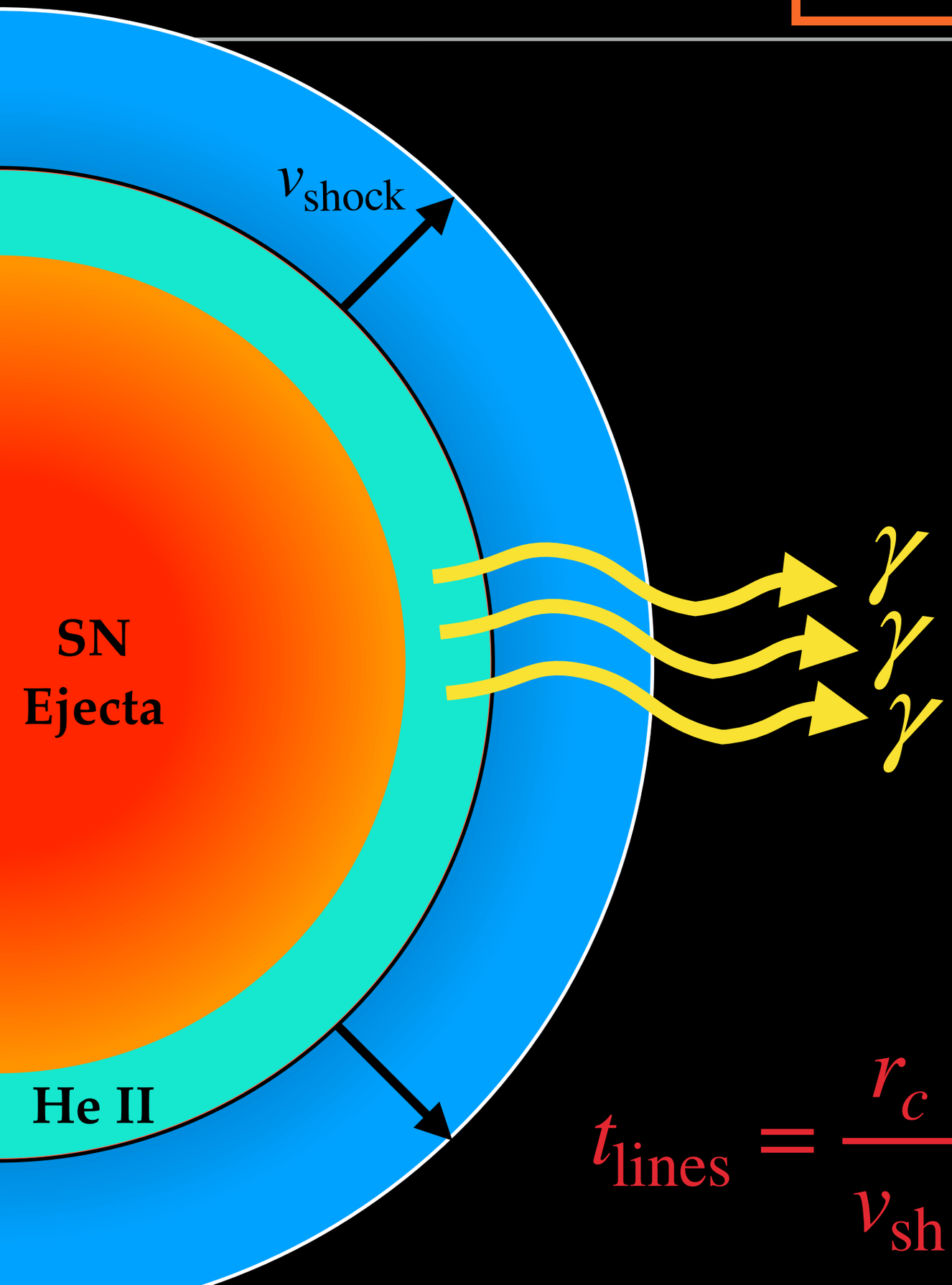


"PHOTO-IONIZATION"

$t_{\rm IIn}$



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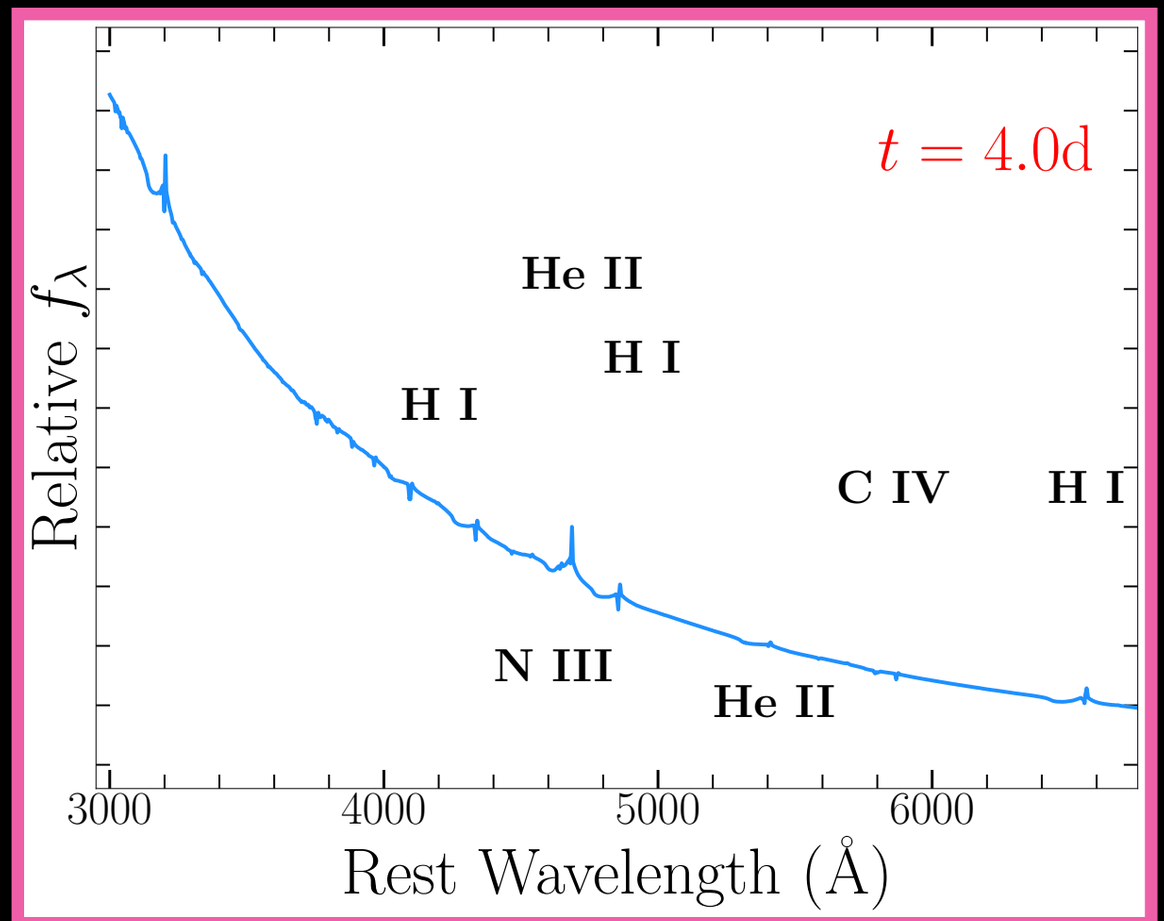


$$t_{\rm lines} = \frac{r_c}{v_{\rm sh}}$$

$t_{\rm II}$

"FLASH" SPECTROSCOPY SAMPLE

Jacobson-Galan+ 2024a

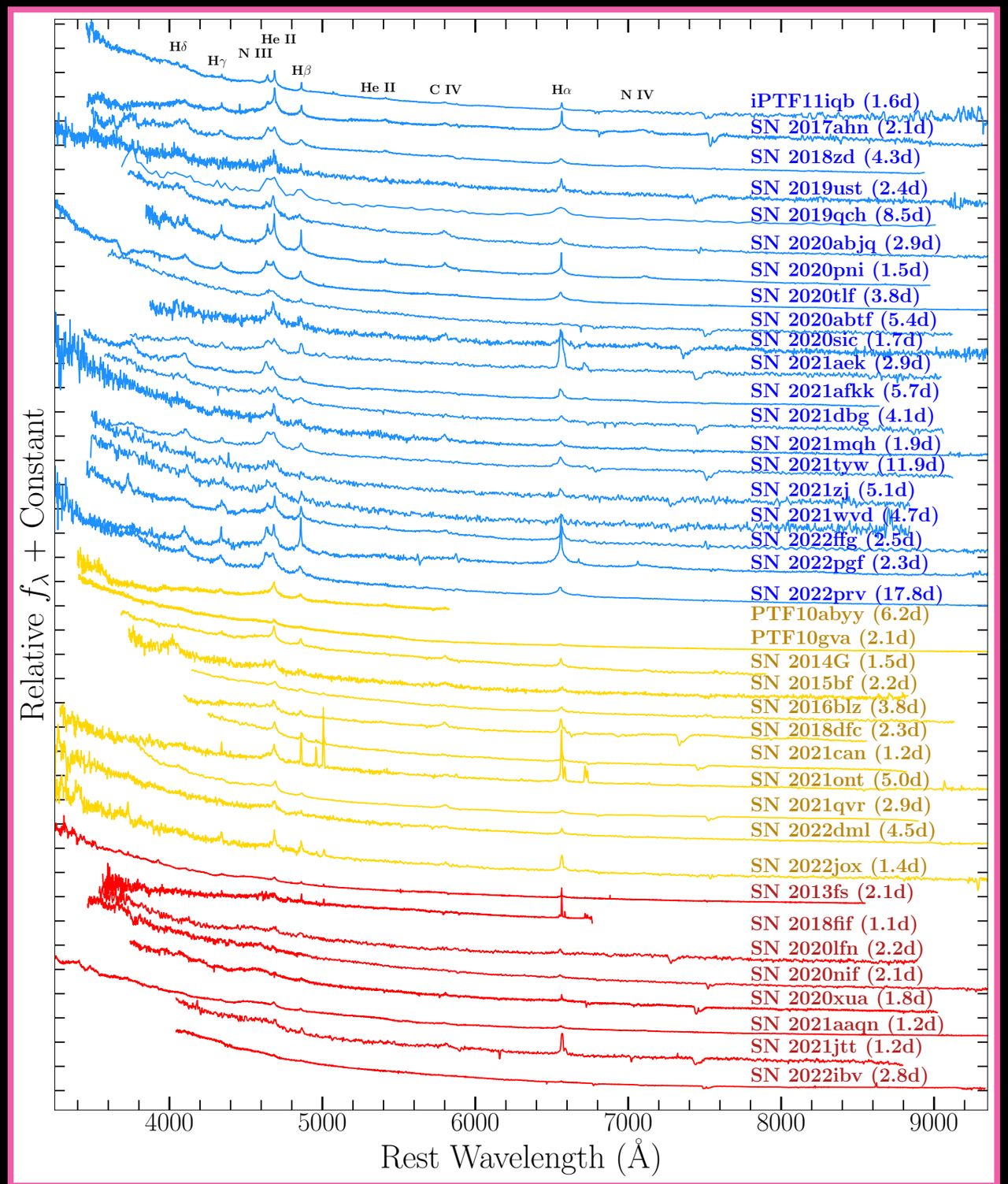
★ Gold/Silver:

- *Swift* UV + IIn-like features (39 SNe)

★ Control:

- *Swift* UV, no IIn-like features (35 SNe)

>900 total spectra & 74 multi-color light curves from the GSP, YSE & other collaborations



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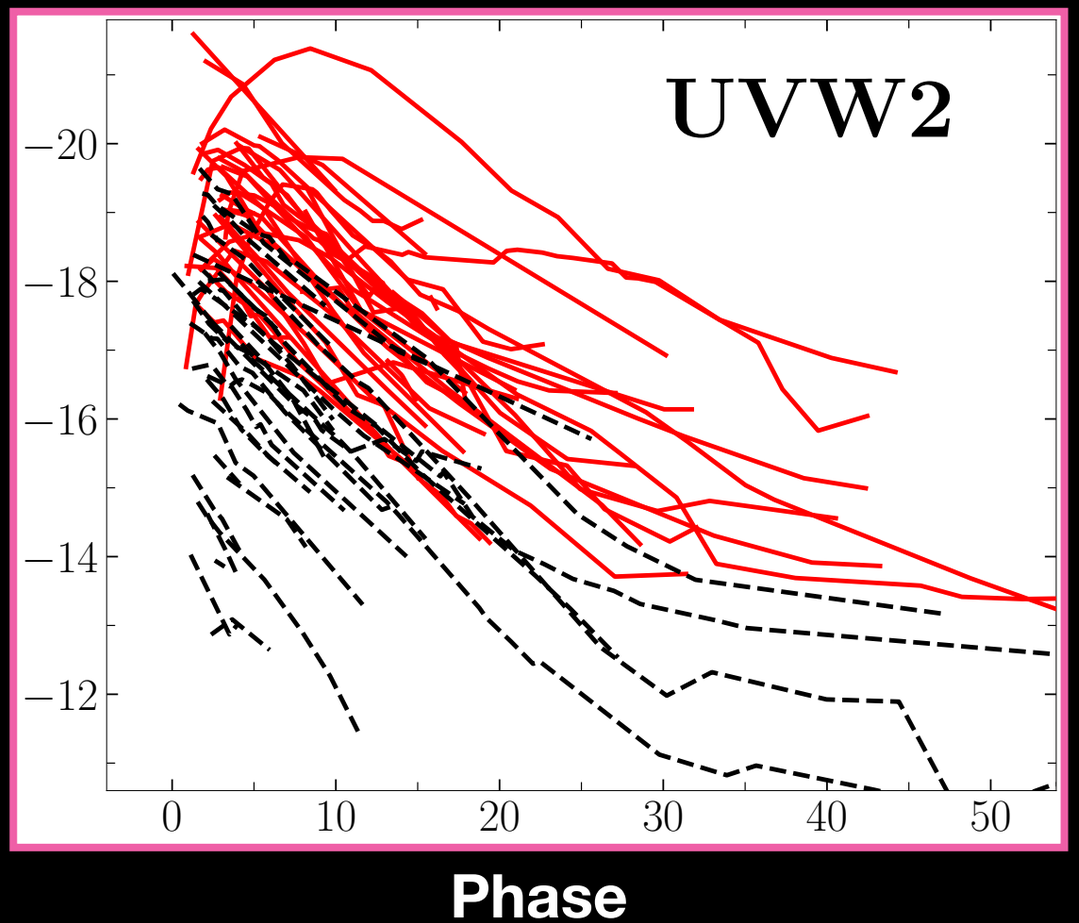
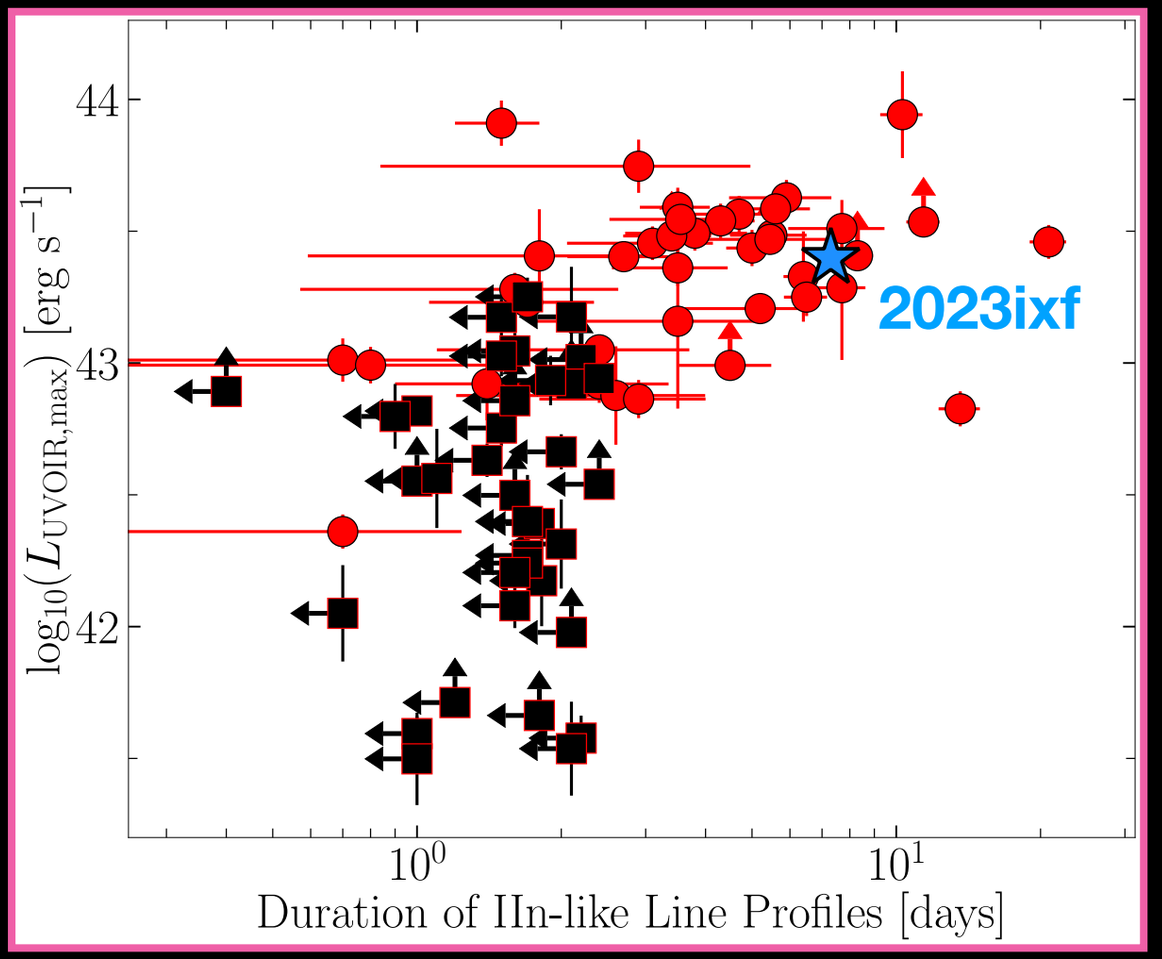




Why *Swift*?

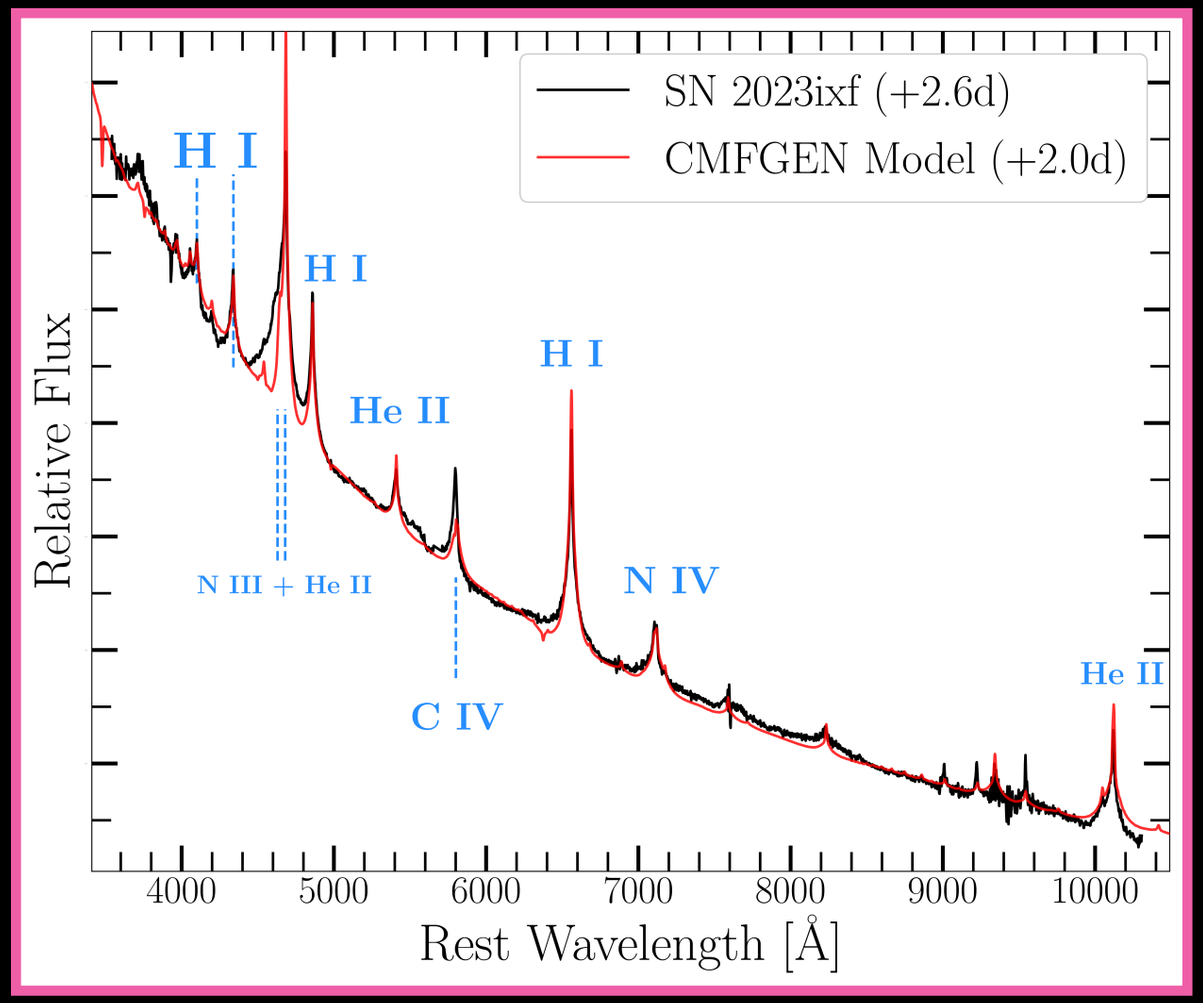
$$T_{\rm eff} \approx \left(\frac{L_{\rm for,sh}}{4\pi\sigma_b R_{\rm CSM}^2}\right)^{1/4} \approx 10^{4-4.5}\ {\rm K}$$

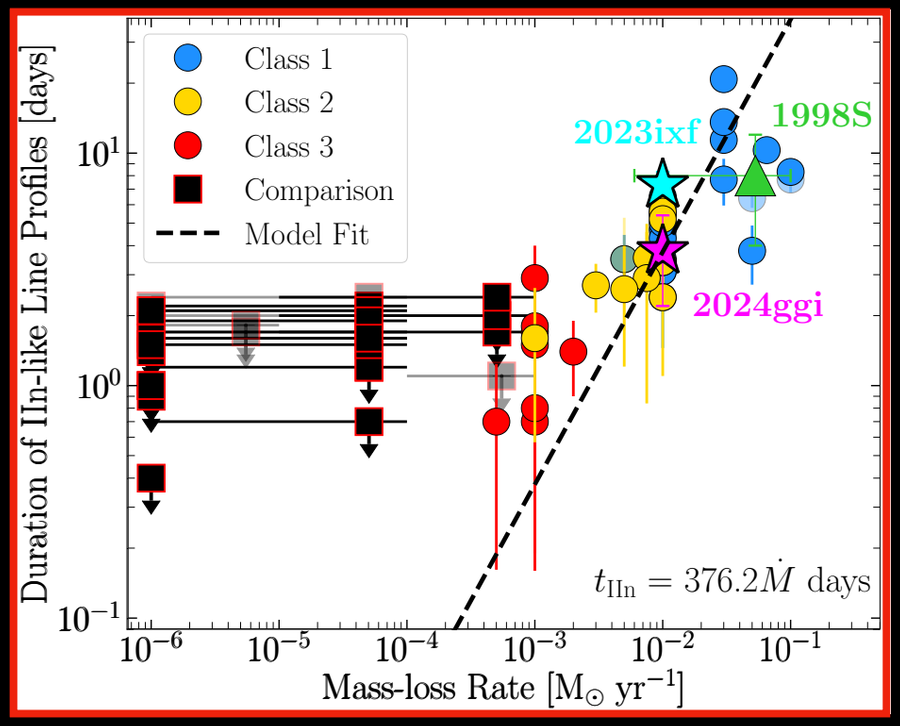
$$L_{\rm for,sh} \propto \dot{M}$$

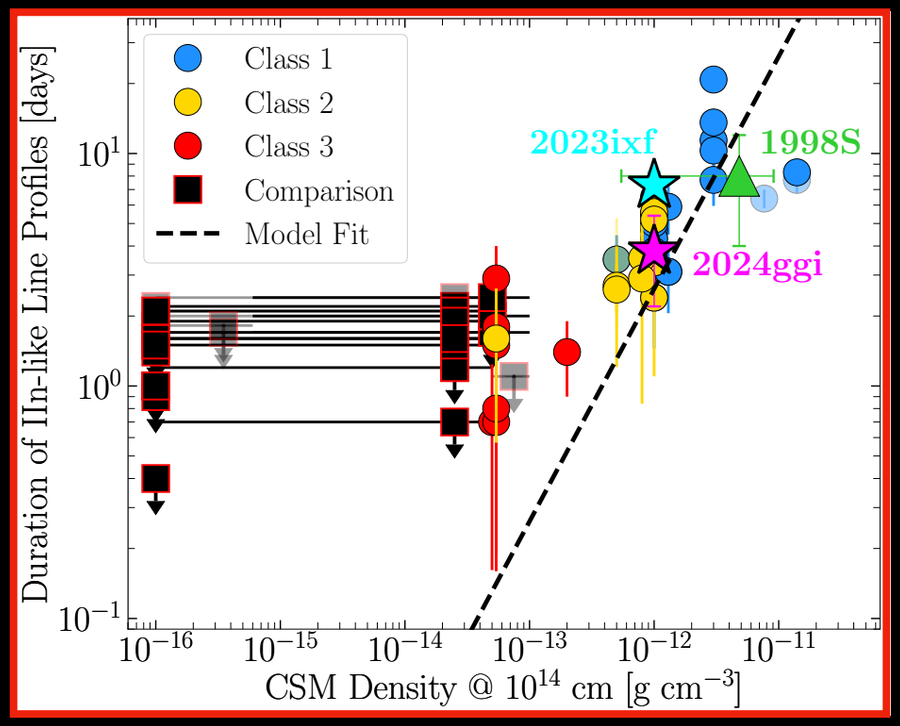
- ★ Enhanced peak UV/bol. luminosities
- ★ Increased rise-times to maximum light
- ★ Increased duration of IIn-like features

RADIATIVE TRANSFER MODELS

Linking observables to progenitor mass-loss and CSM structure



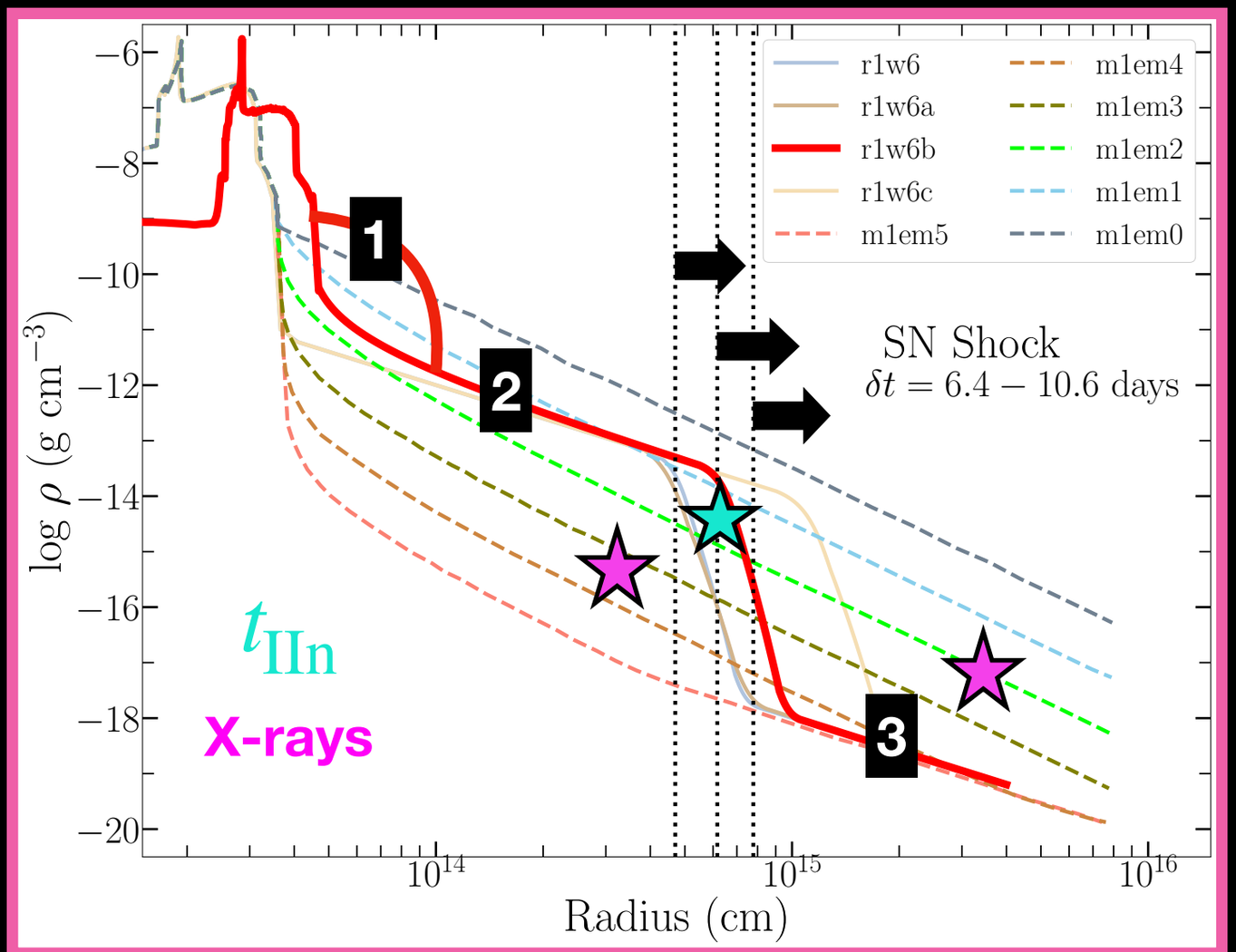


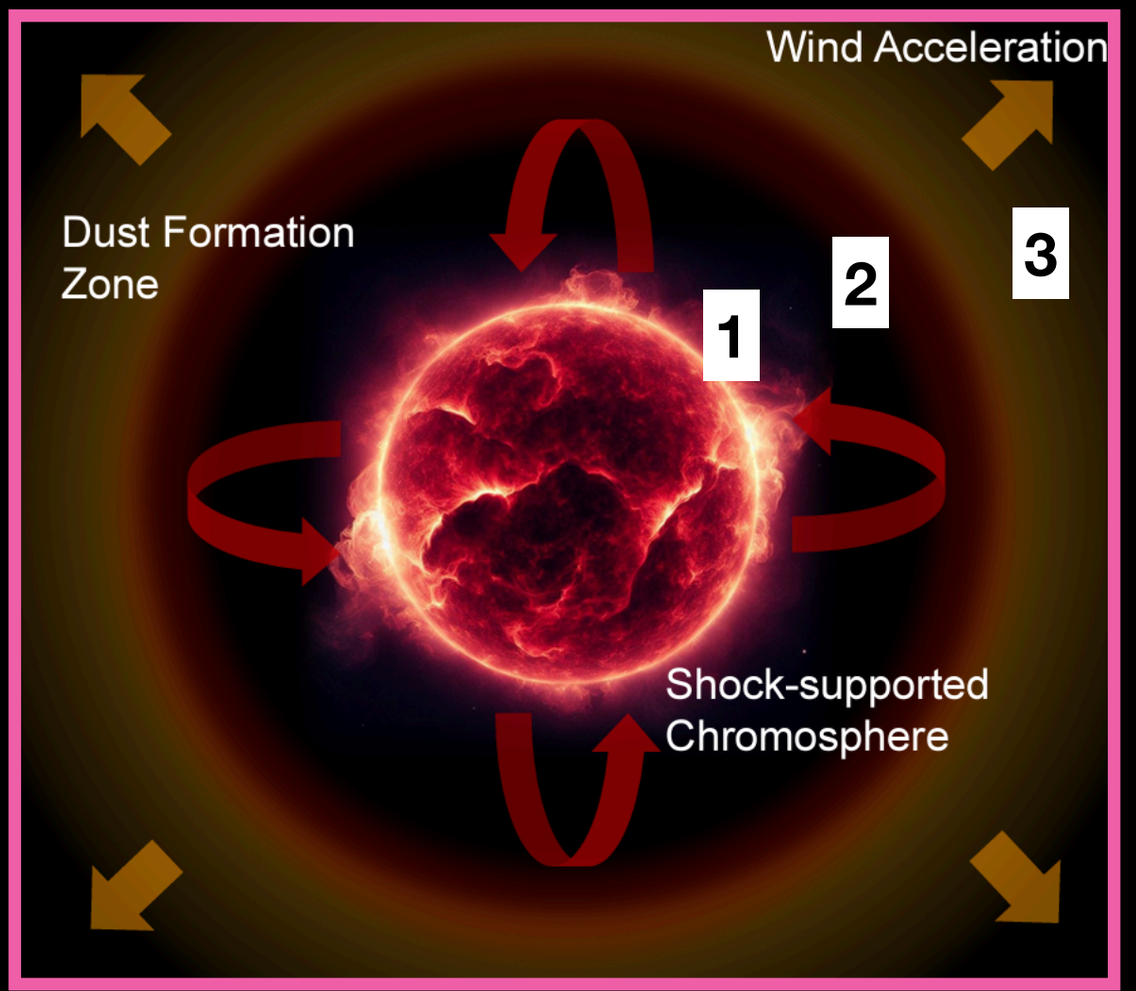


Dessart & WJG 2023; WJG+ 2023, 2024a,b

A PHYSICAL PICTURE OF A RED SUPERGIANT BEFORE COLLAPSE

1. Densest CSM: Extended SBO + rising ionization ($r < 10^{14}$ cm)
2. Pretty Dense CSM: Rising ionization + IIn-like signature ($r < 7 \times 10^{14}$ cm)
3. Extended Wind: Sustained CSM-interaction + SN II profiles ($r > 10^{15}$ cm)

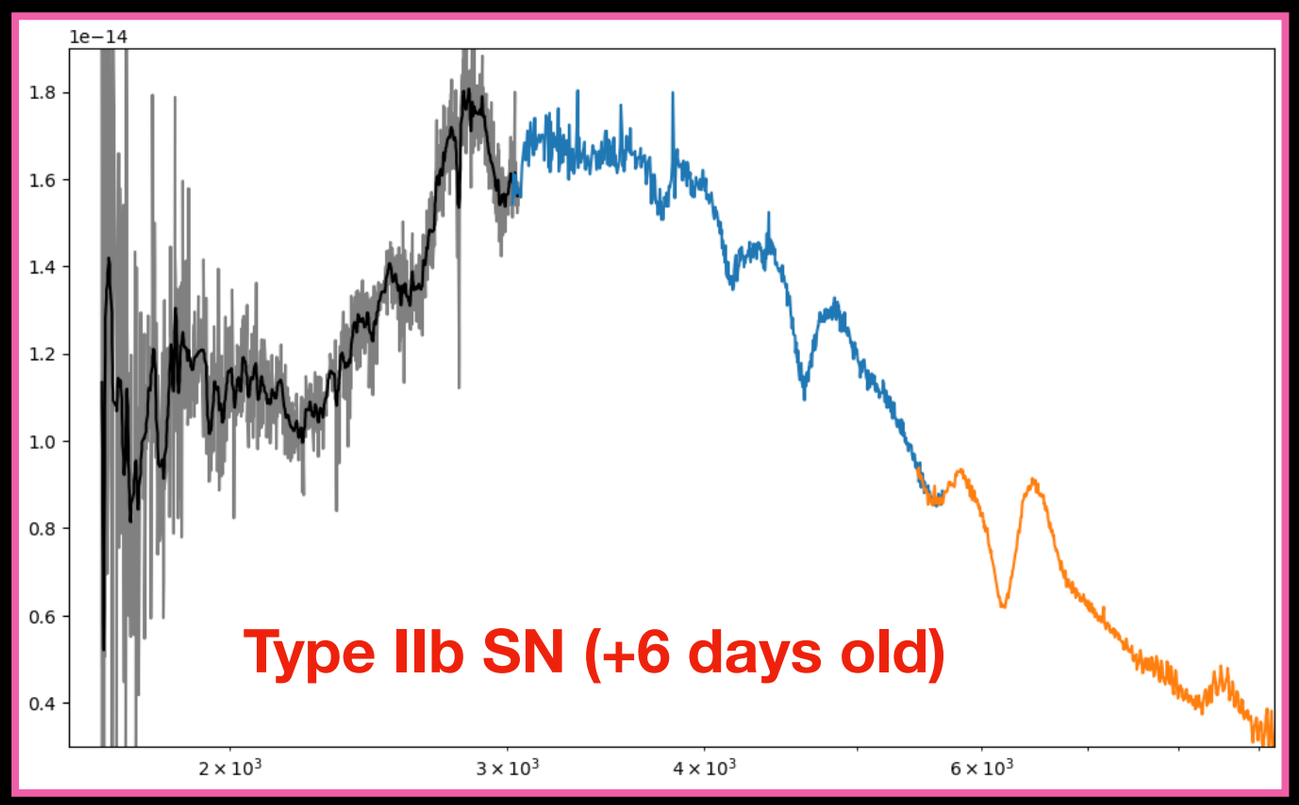


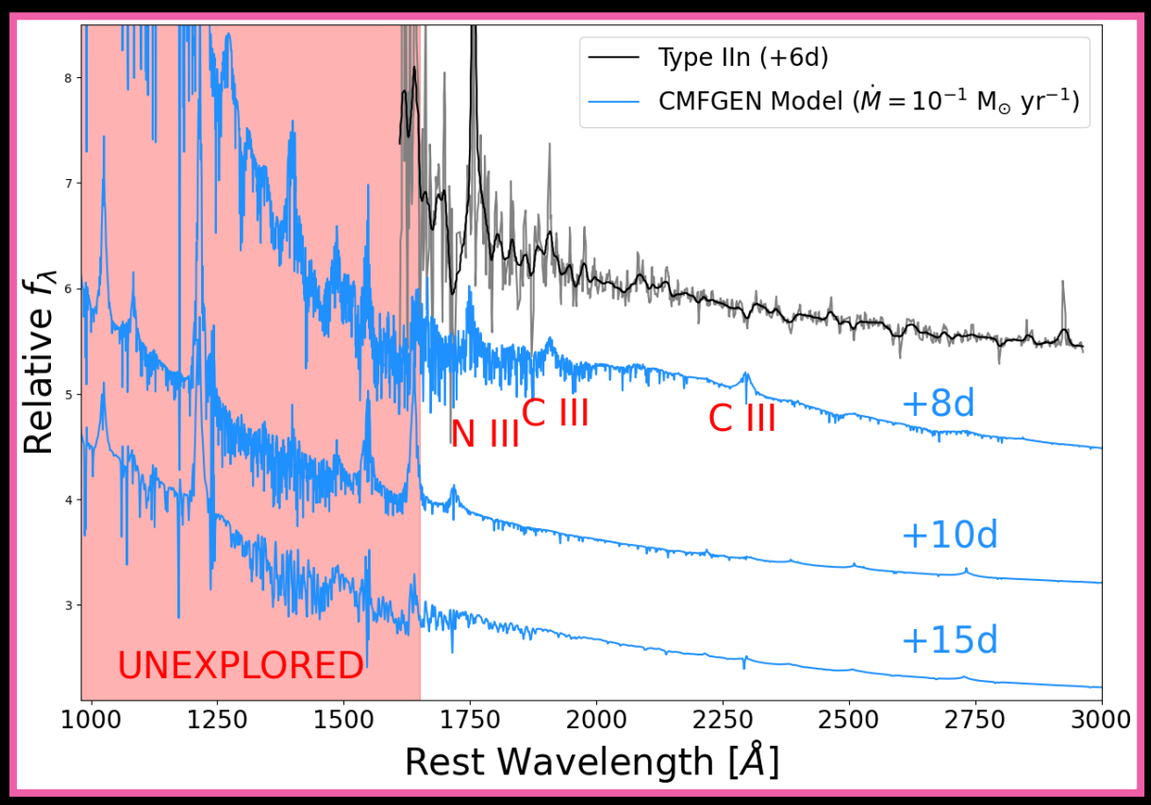


Fuller & Tsuna 2024

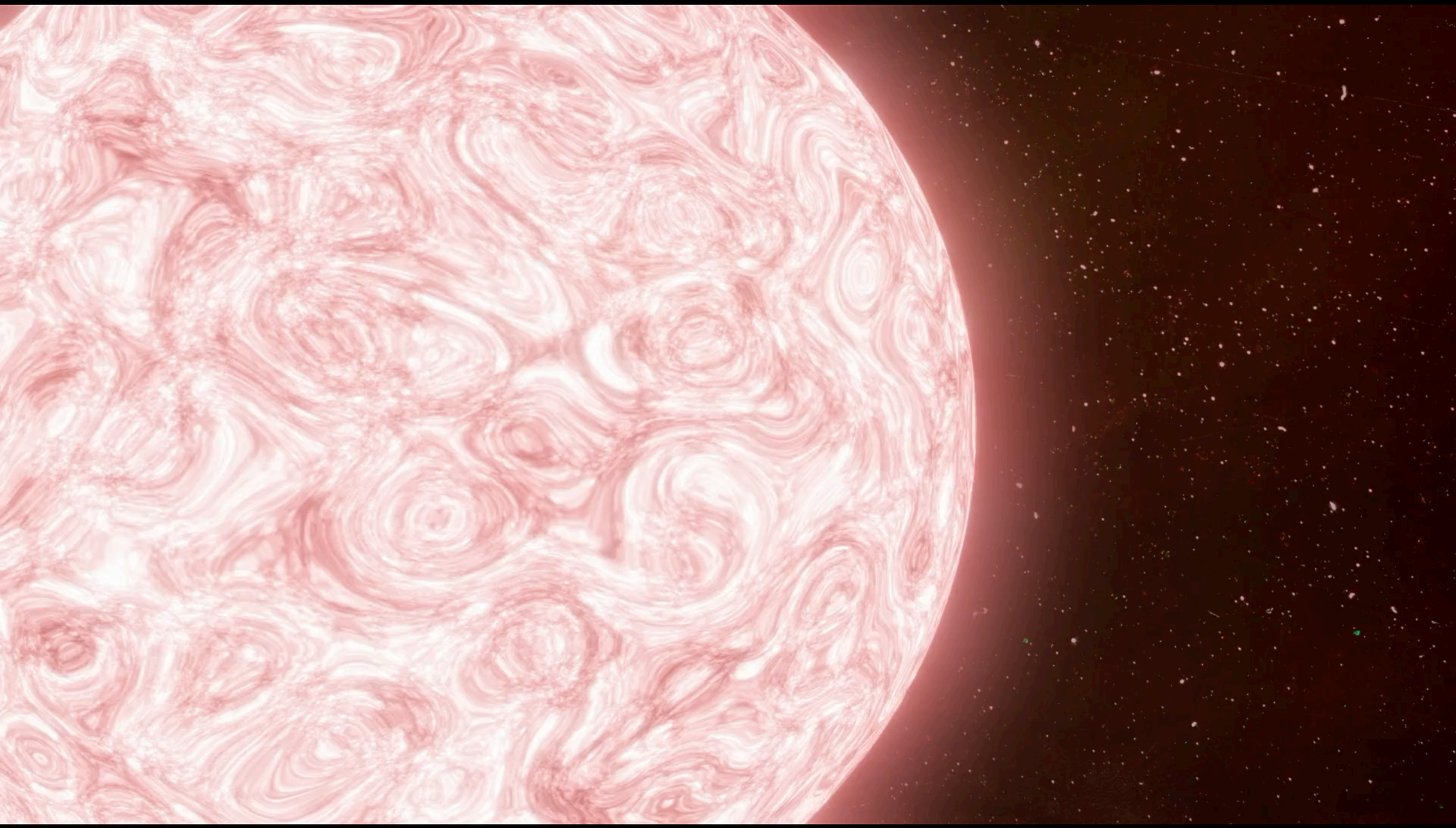
FUTURE: UV + X-RAY

- ★ Systematic discovery and automated follow-up of infant SNe (ZTF "BTSBot-nearby" , Rehemtulla+ 2024)
- ★ "Flash" UV spectroscopy using ZTF + *HST* + *Swift* ("ZTF Flexible Weekends")
- ★ Rapid follow-up in the UV (*Swift*-UVOT Priority 0, *ULTRASAT, UVEX)* and X-rays (*Swift*-XRT, Einstein Probe, AXIS Probe)

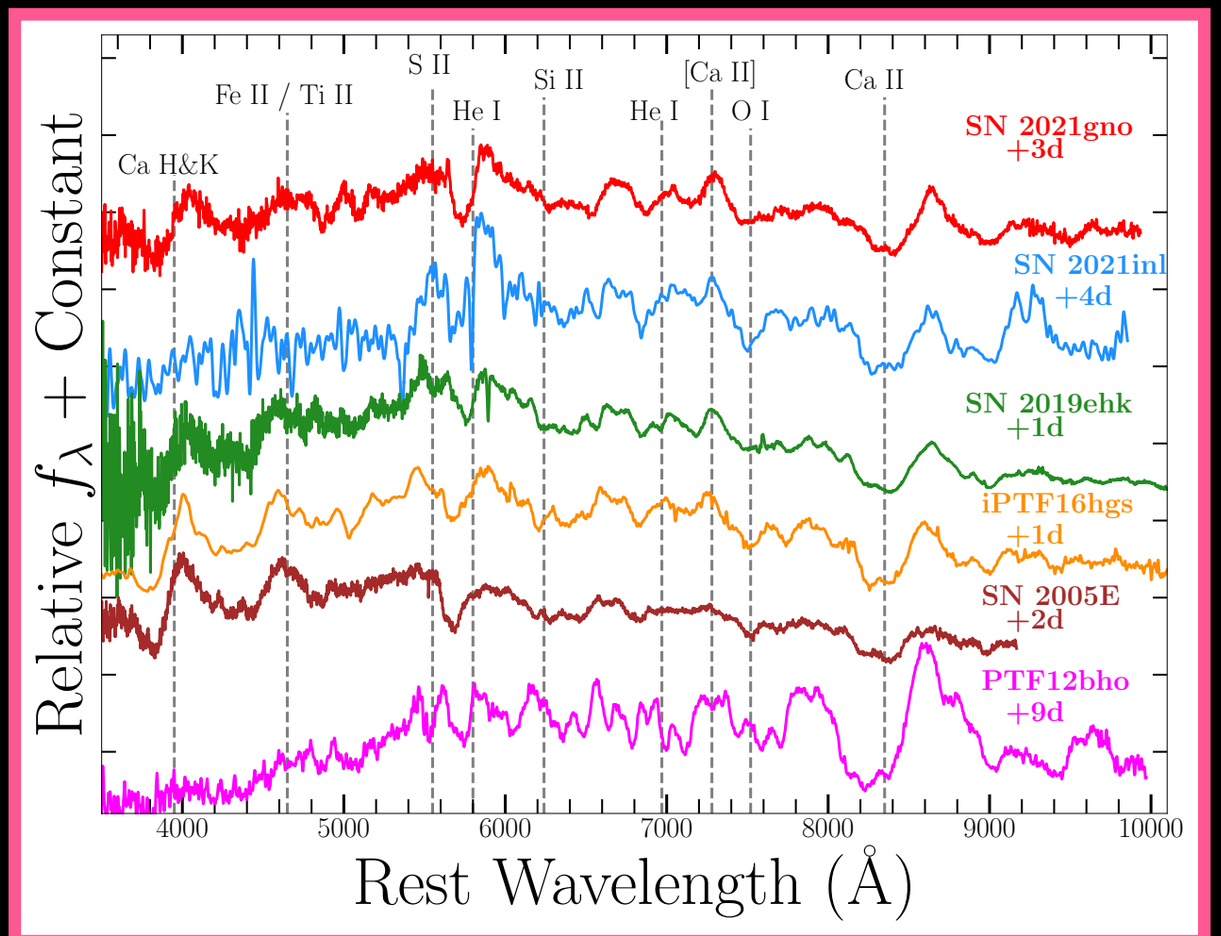


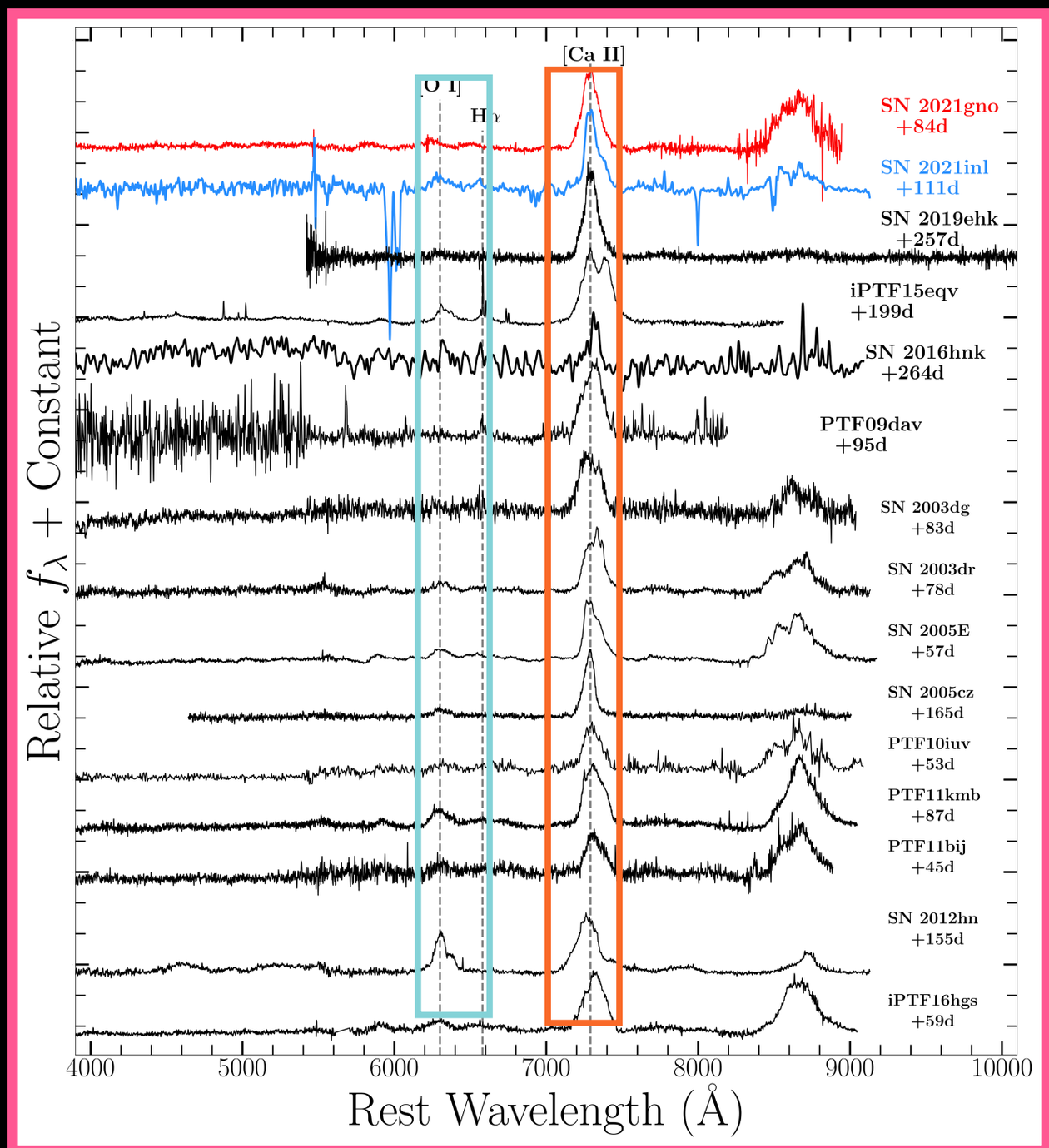


HOW CAN WE IMPROVE EARLY-TIME SN SCIENCE WITH SPACE TELESCOPES?



SPECTROSCOPIC EVOLUTION





Characteristics:

- ★ Type I spectra + Helium (sometimes)
- ★ Velocities: 6000 - 11,000 km/s
- ★ Strong Calcium features

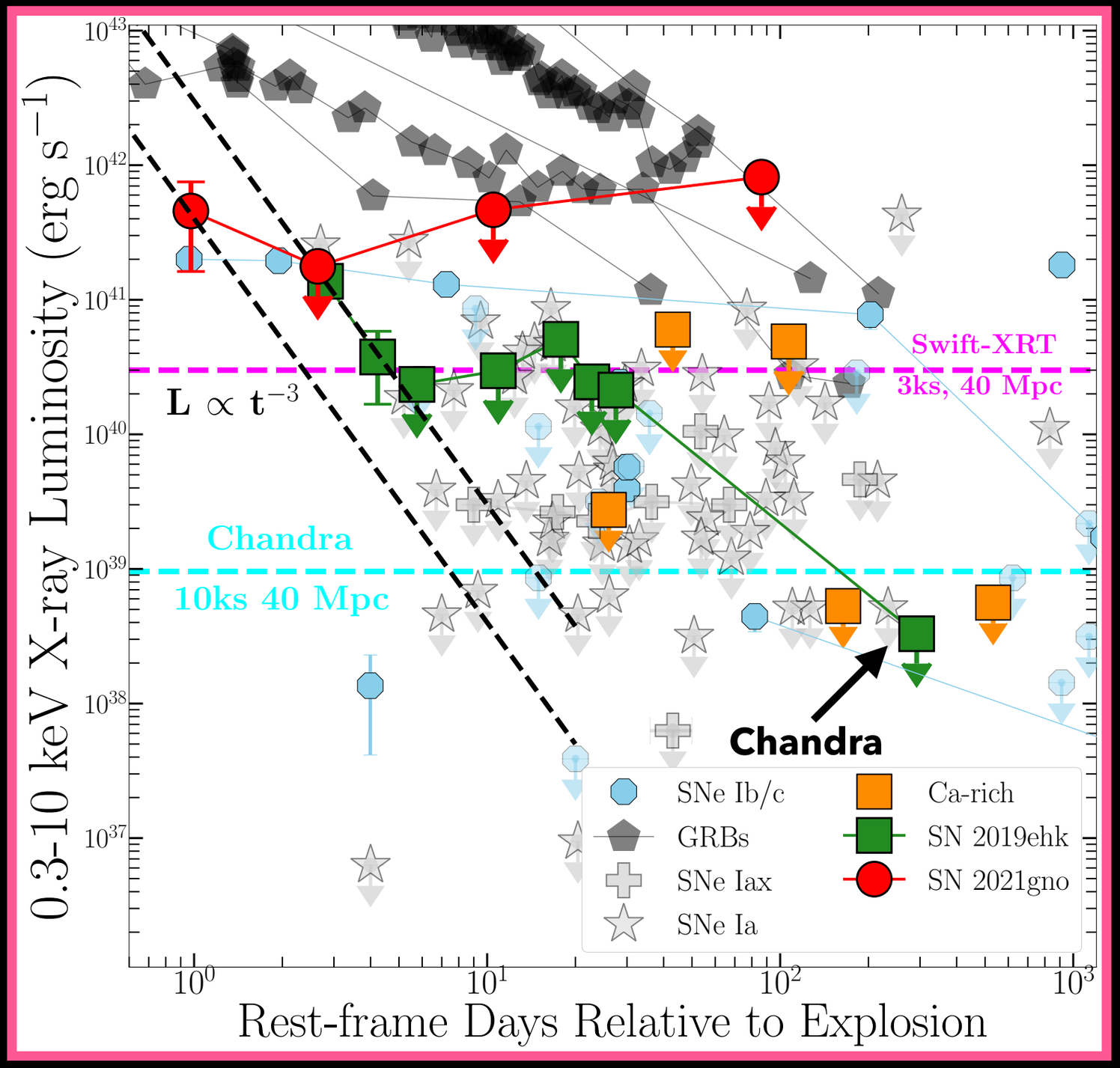
[Ca II] / [O I] > 2

"Calcium-rich" –> "Calcium-strong"

Shen+ 2019

CALCIUM-RICH X-RAY PHASE SPACE

- ★ No observations at $t < 20$ days
- ★ SNe 2019ehk & 2021gno are the only Ca-rich transients with X-ray detections
- ★ Luminous, fast-fading X-rays detected by *Swift*-XRT
- ★ *Chandra* provided deepest X-ray observation of Ca-rich SN
- ★ Indicates shock interaction with confined CSM



DISCUSSION QUESTIONS:

★ What ToO science cases are we are interested in? Timescales? Wavelengths?

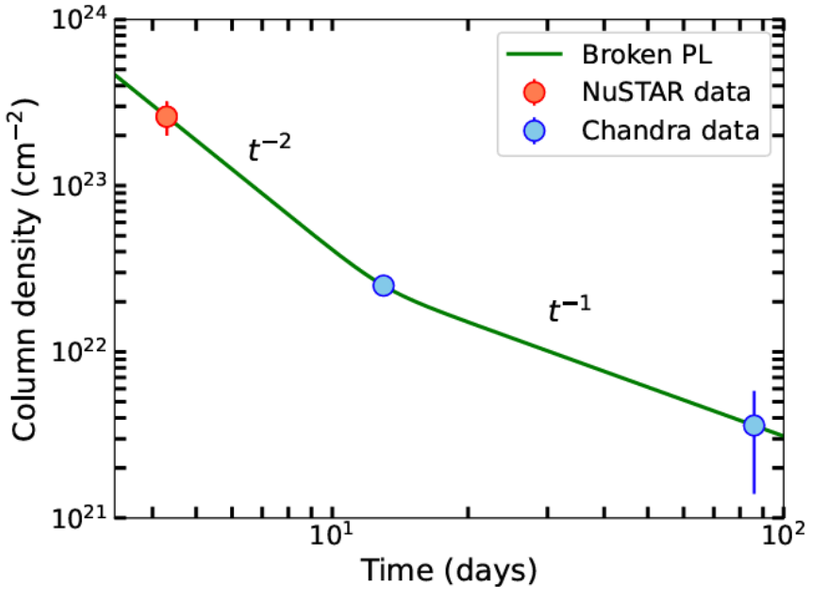
★ Can/should approved ToO programs collaborate on triggers?

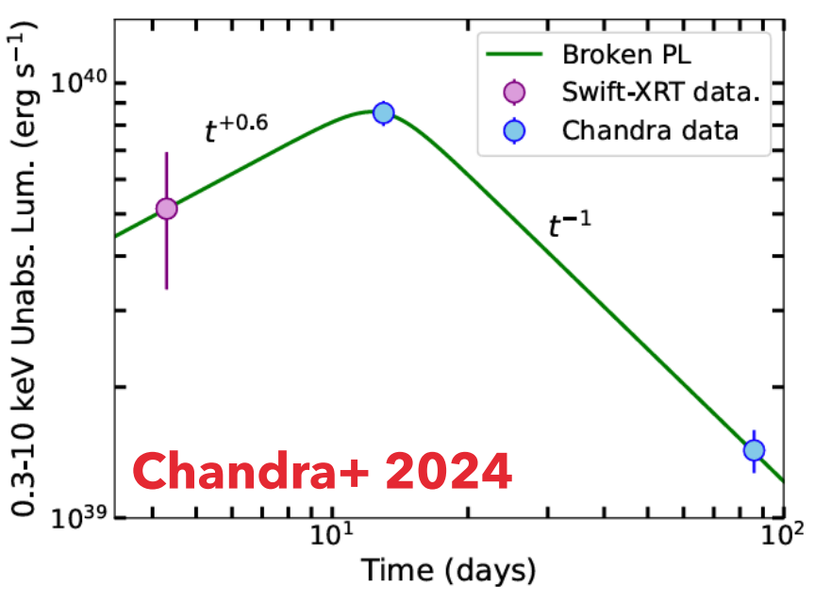
★ What telescope synergies can be explore for space telescope ToOs?

★ More public data?

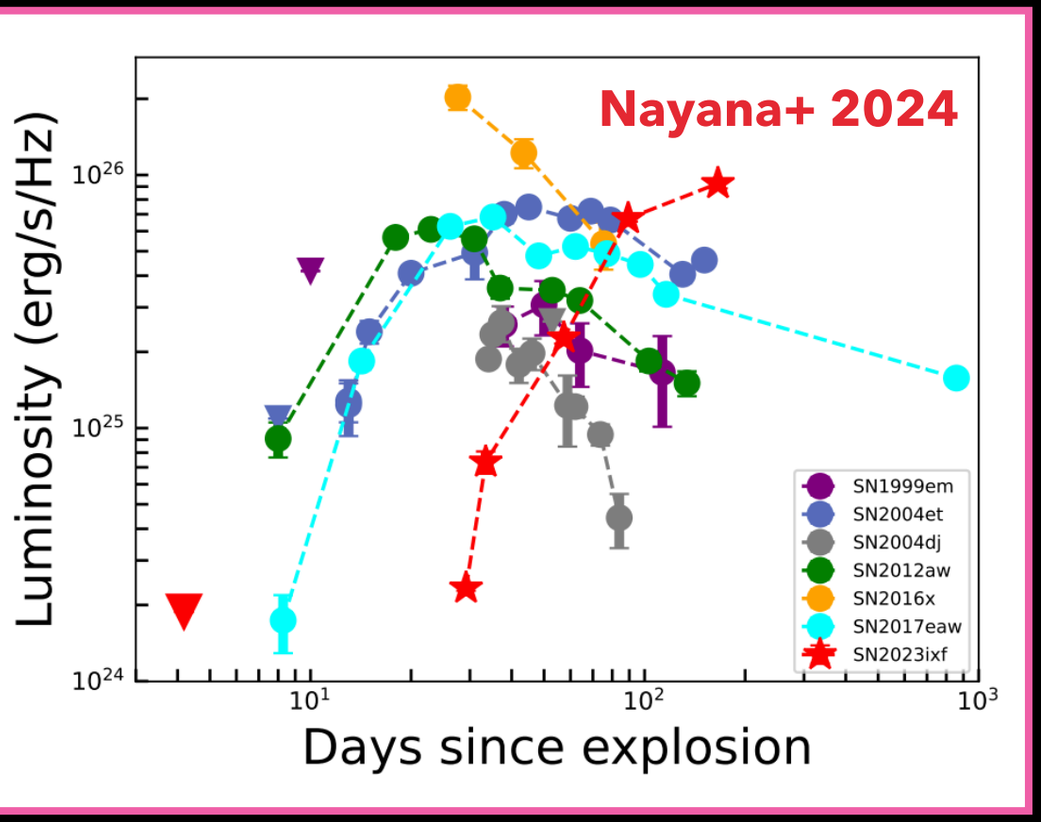
★ “Once in a decade SN” community triggers?

TYPE II SUPERNOVA X-RAY + RADIO EMISSION



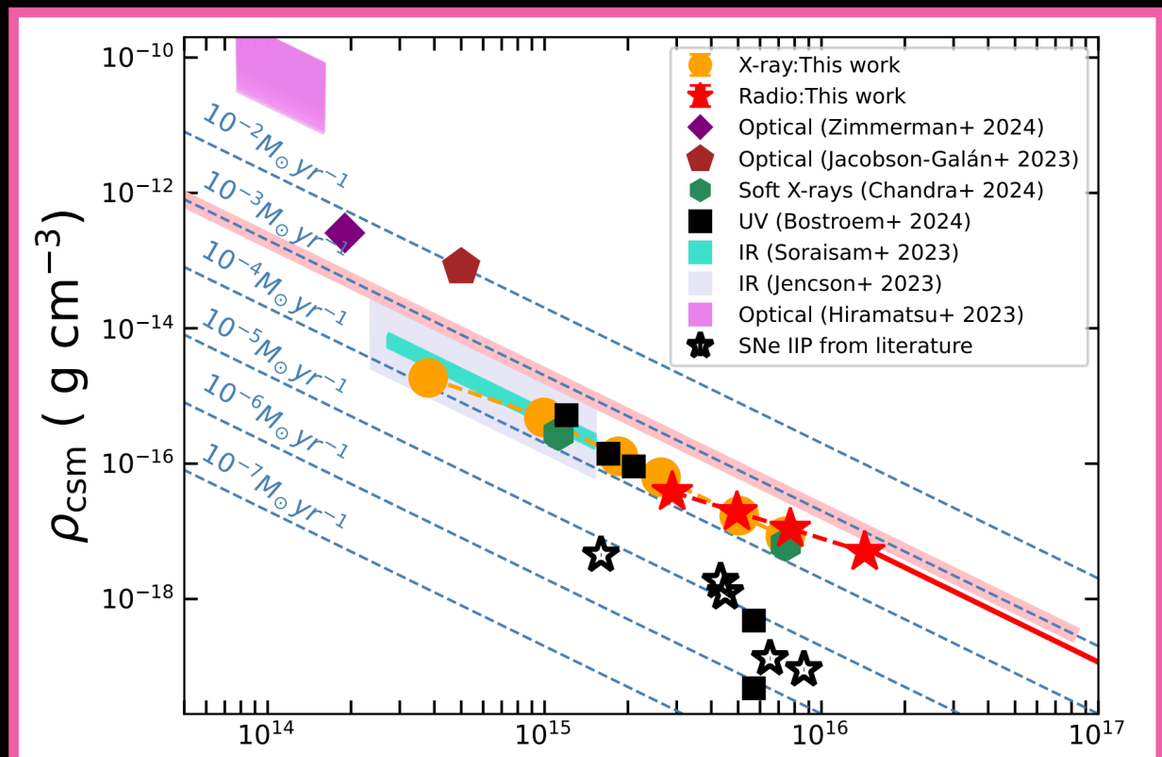


Decreasing CSM density -> Rising X-ray Emission

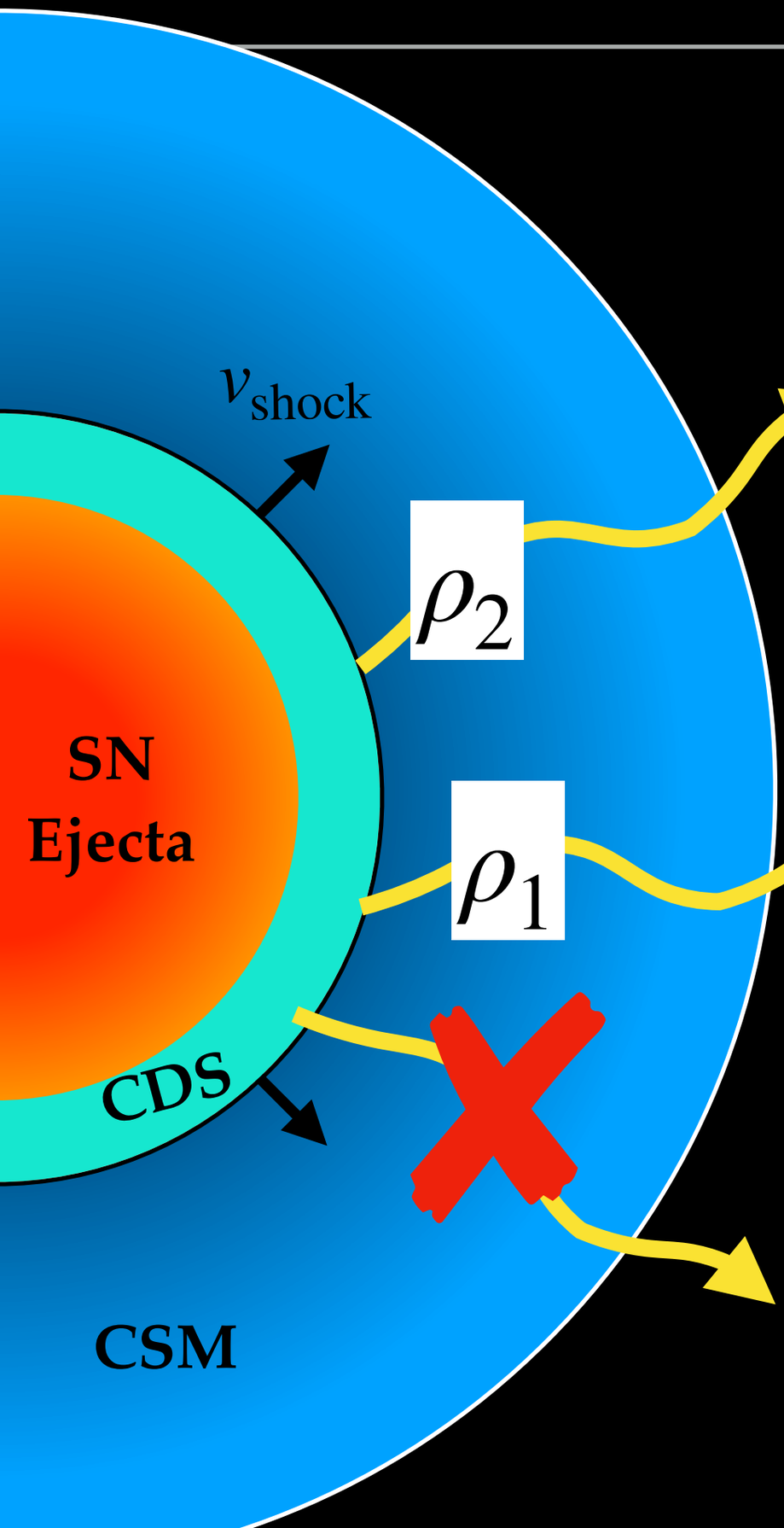


Absorption of early-time radio emission

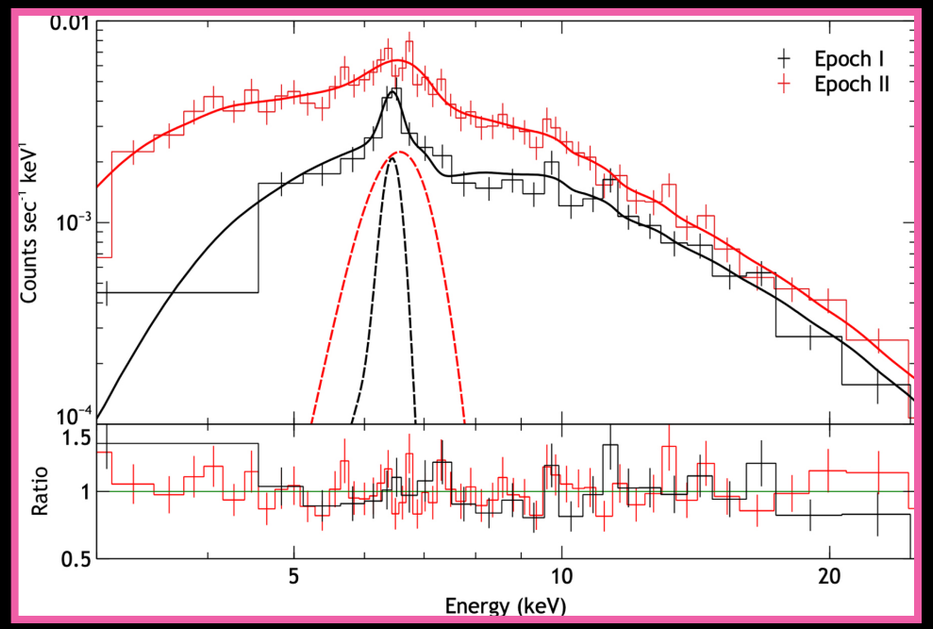
Probing 100-1000s of years of mass-loss:



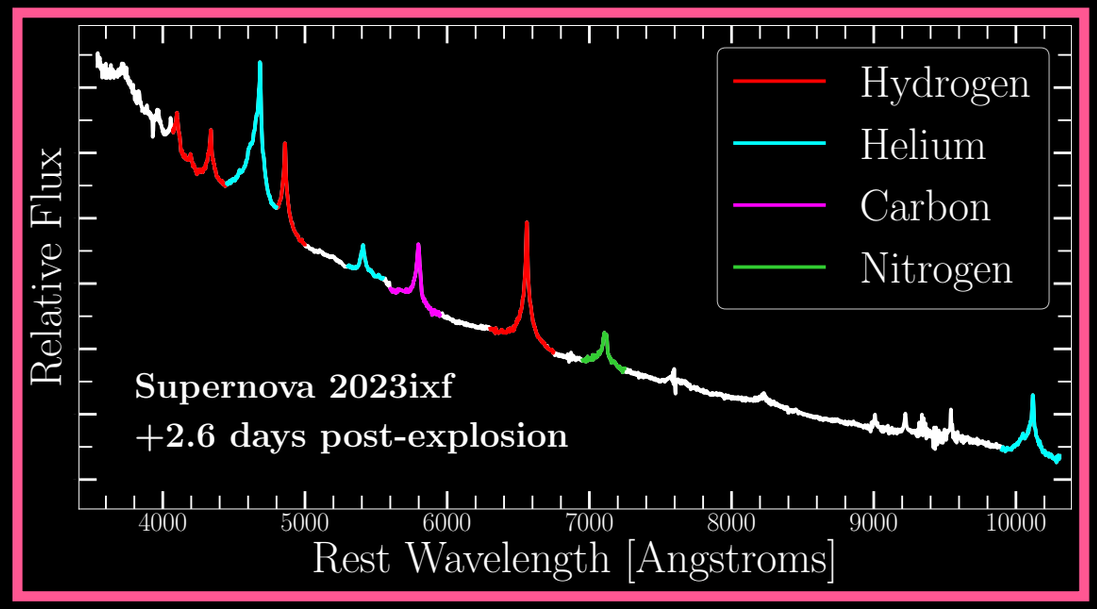
Nayana+ 2024



$\gamma_{\rm xray}$



$\gamma_{\rm IIn}$



$\gamma_{\rm radio}$

$\rho_2 < \rho_1$

$t_{\rm IIn}$

EXAMPLE CASE:

$\dot{M} = 10^{-2}\ \mathrm{M_\odot yr^{-1}}, r \approx 10^{15}\ \mathrm{cm}$

$T_e \sim 10^{4.5}\ \mathrm{K}$

v_{shock}

SN Ejecta

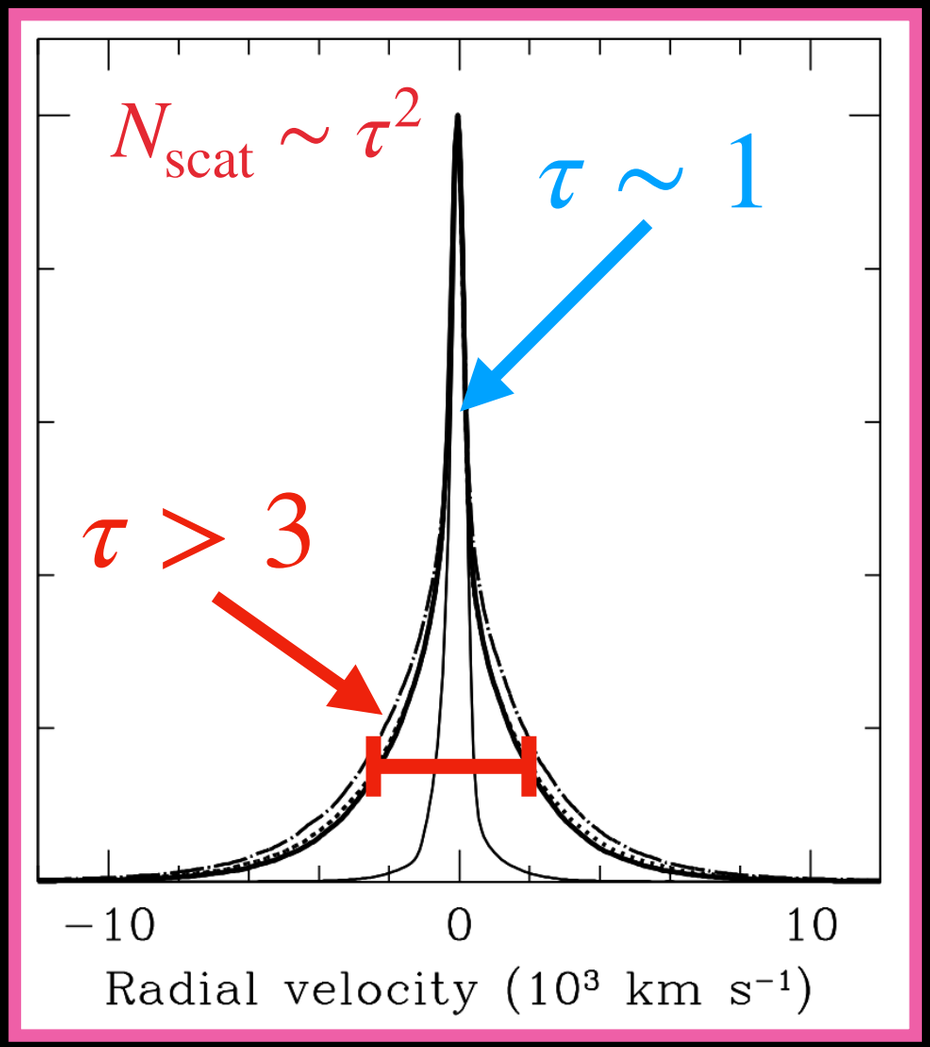
γ

H II

γ

γ

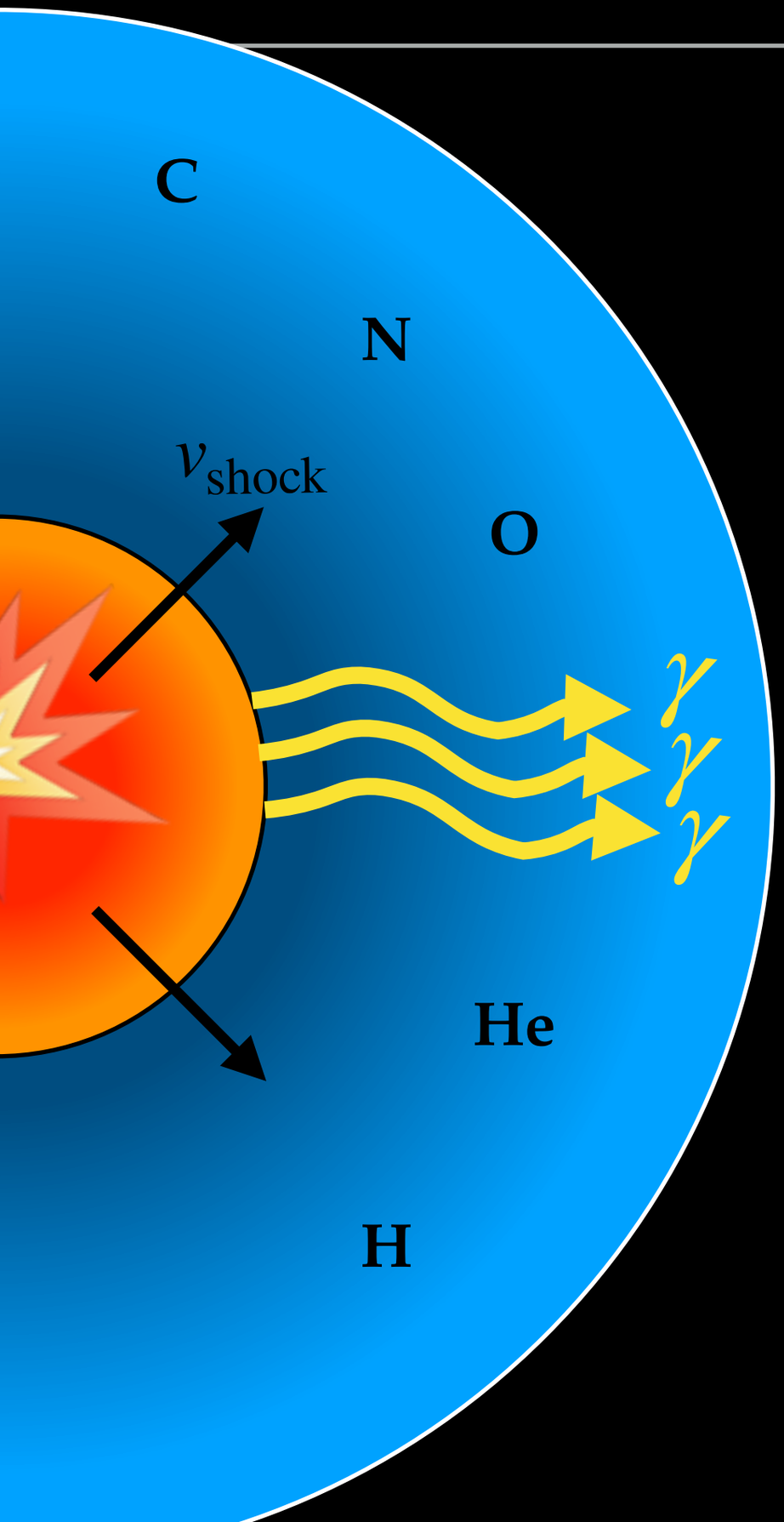
$\tau \sim 3 - 10$



$$\frac{\sigma_\nu}{\nu_0} \approx \tau \frac{\mathrm{v_e}}{c}$$

$$\mathrm{v}_e \approx 10^3\ \mathrm{T}_{4.5}^{1/2}\ \mathrm{km/s}$$

t_{IIn}



LIMITING CASES:

1. $\dot{M} = 10^{-6}\ \mathrm{M_\odot yr^{-1}}, r \approx 10^{15}\ \mathrm{cm}$

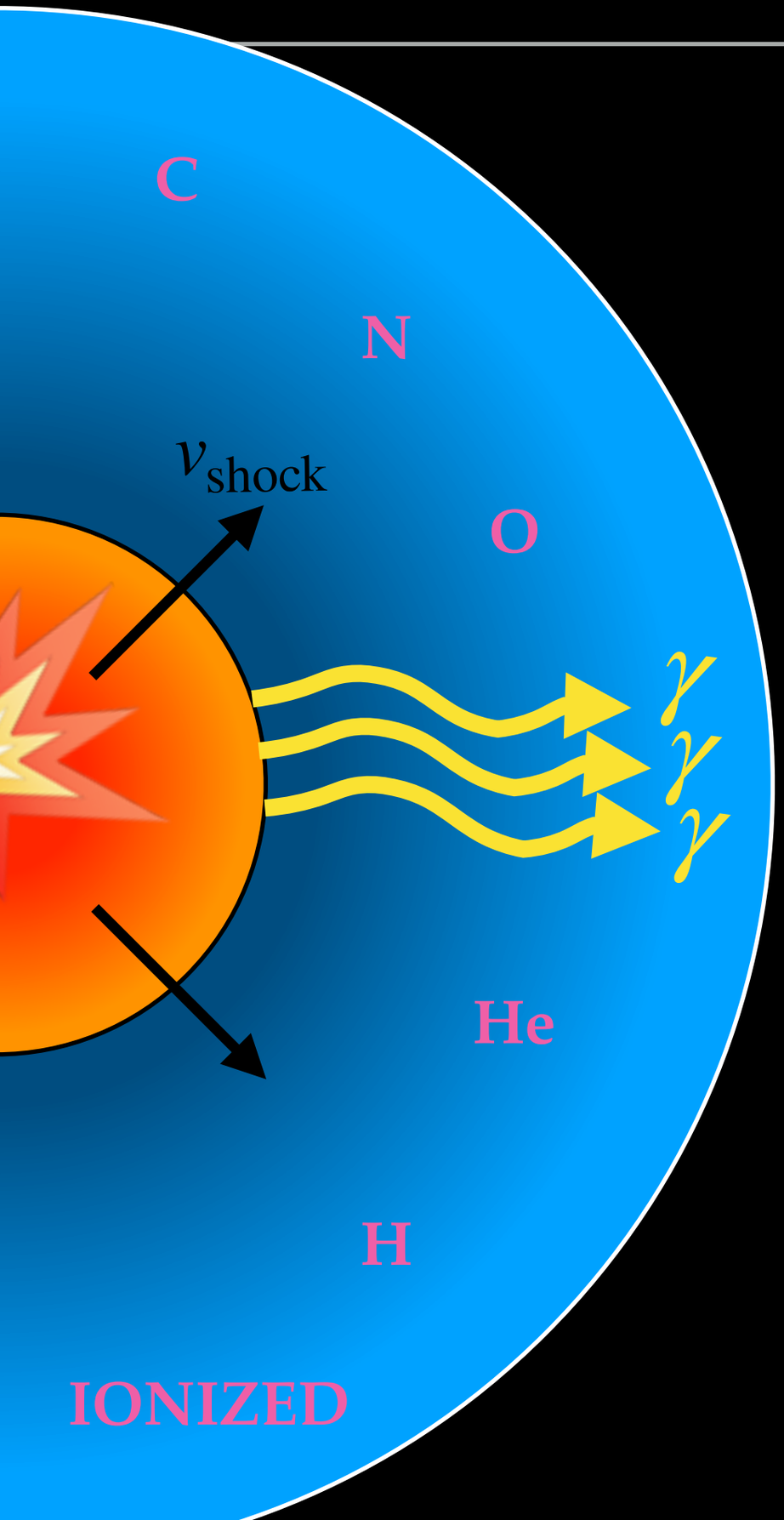
$$\tau_{\rm SBO} \sim \frac{c}{v_{\rm sh}} \sim 30\ ;\ (v_{\rm ej} \sim 3 \times 10^4\ \mathrm{km/s})$$

$$T_{\rm max} \approx 6 \times 10^5 \left(\frac{R_\star}{500 R_\odot}\right)^{-0.54}\ \mathrm{K}$$

$$E_{\rm rad} \approx 2 \times 10^{48} \left(\frac{R_\star}{500 R_\odot}\right)^{1.74}\ \mathrm{erg/s}$$

(Matnzer & McKee 1999)

$t_{\rm SBO}$



LIMITING CASES:

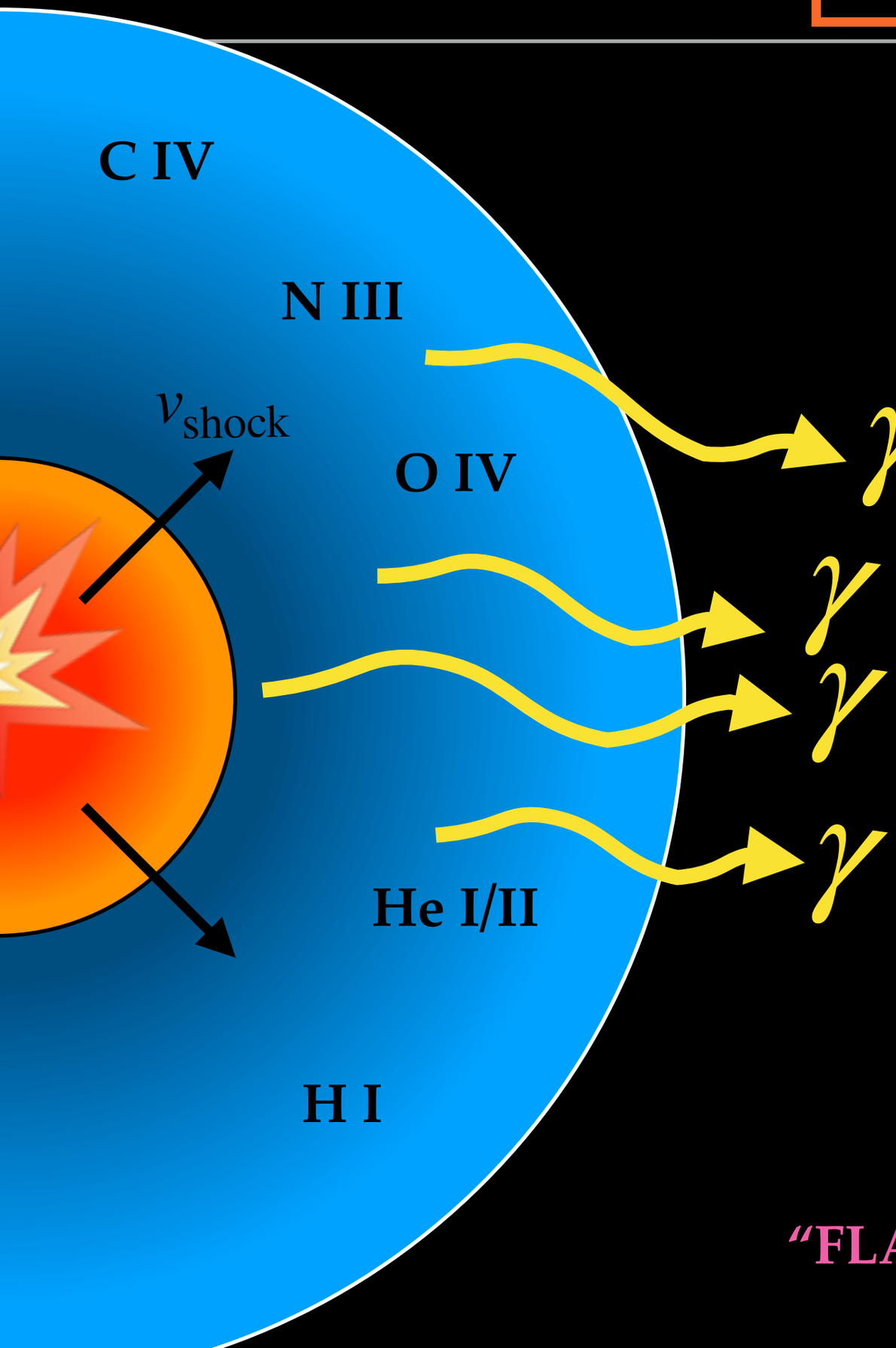
1. $\dot{M} = 10^{-6}\ \mathrm{M_\odot yr^{-1}}, r \approx 10^{15}$ cm

$$t_{\rm rec} = [\alpha_{ij}\ n_e]^{-1}\ (r = r_{sh})$$

$$t_{\rm ion} = \frac{V\ n_e}{Q}$$

In steady state : $t_{\rm ion} = t_{\rm rec} \approx$ hrs

$t_{\rm flash}$



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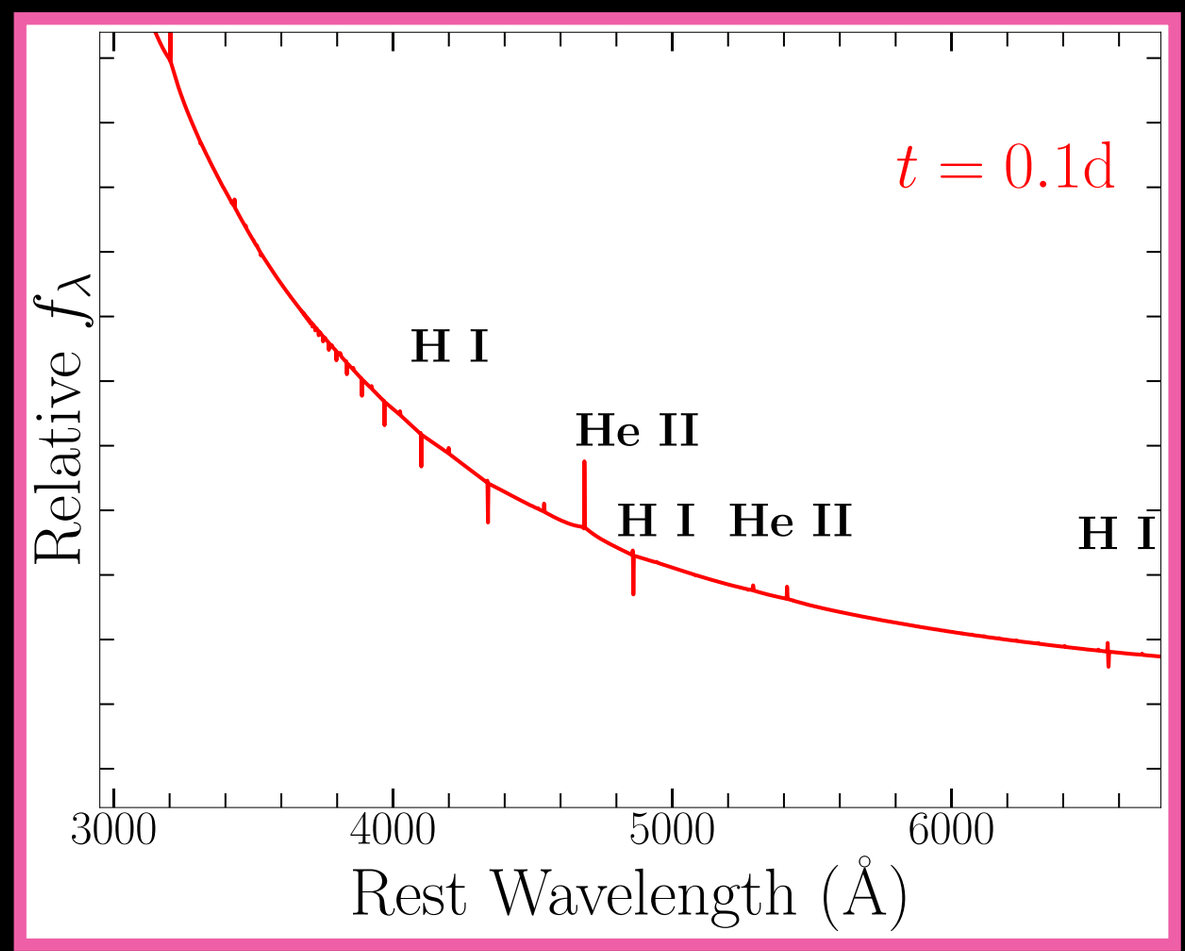

"FLASH IONIZATION"

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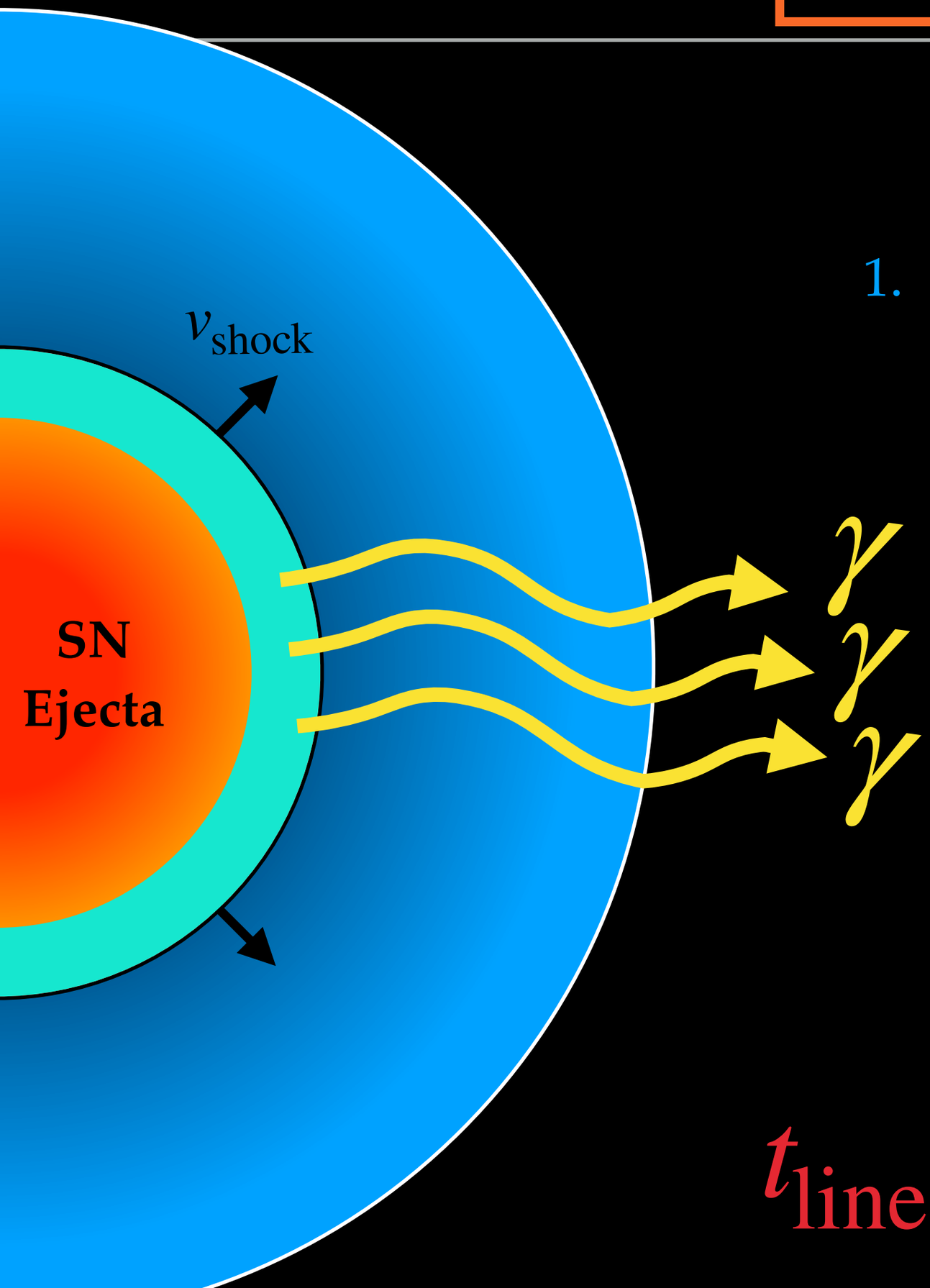

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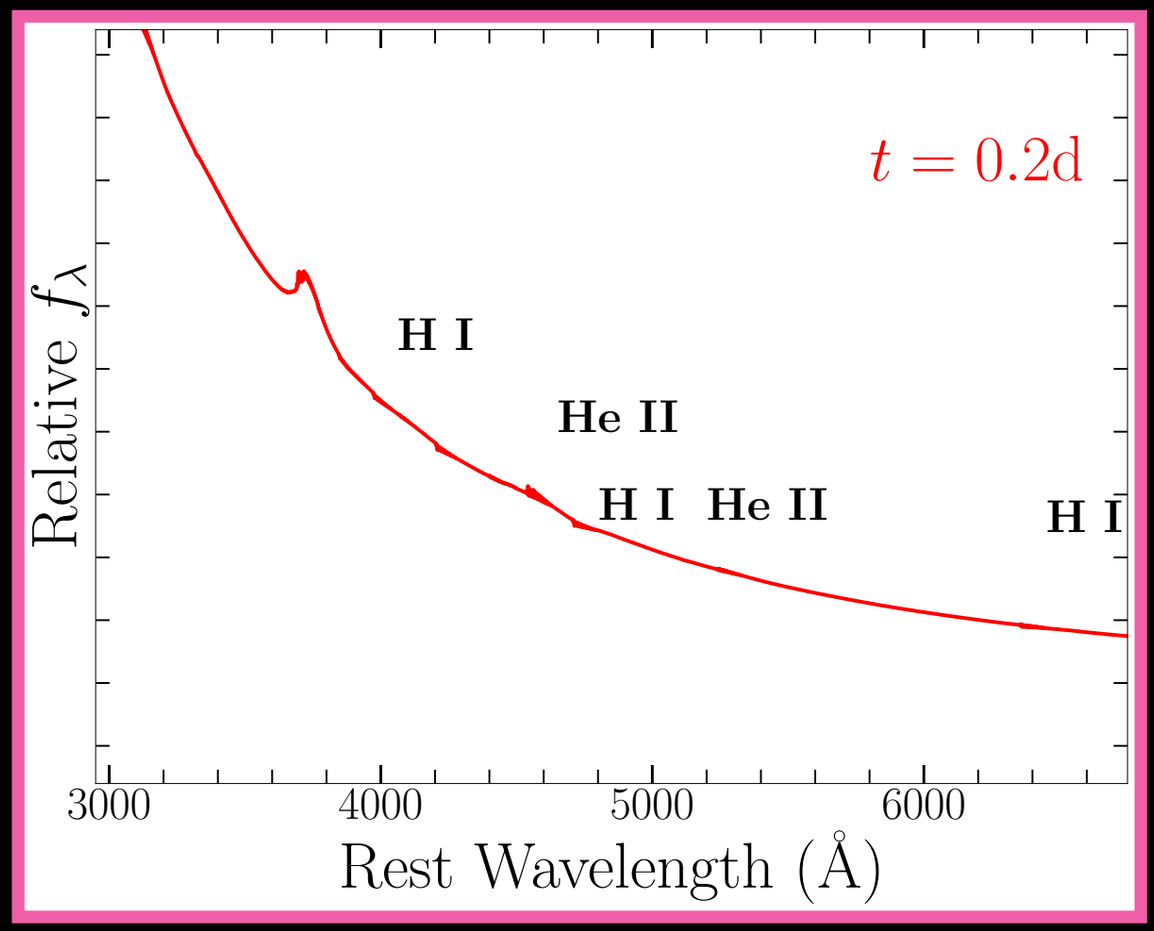
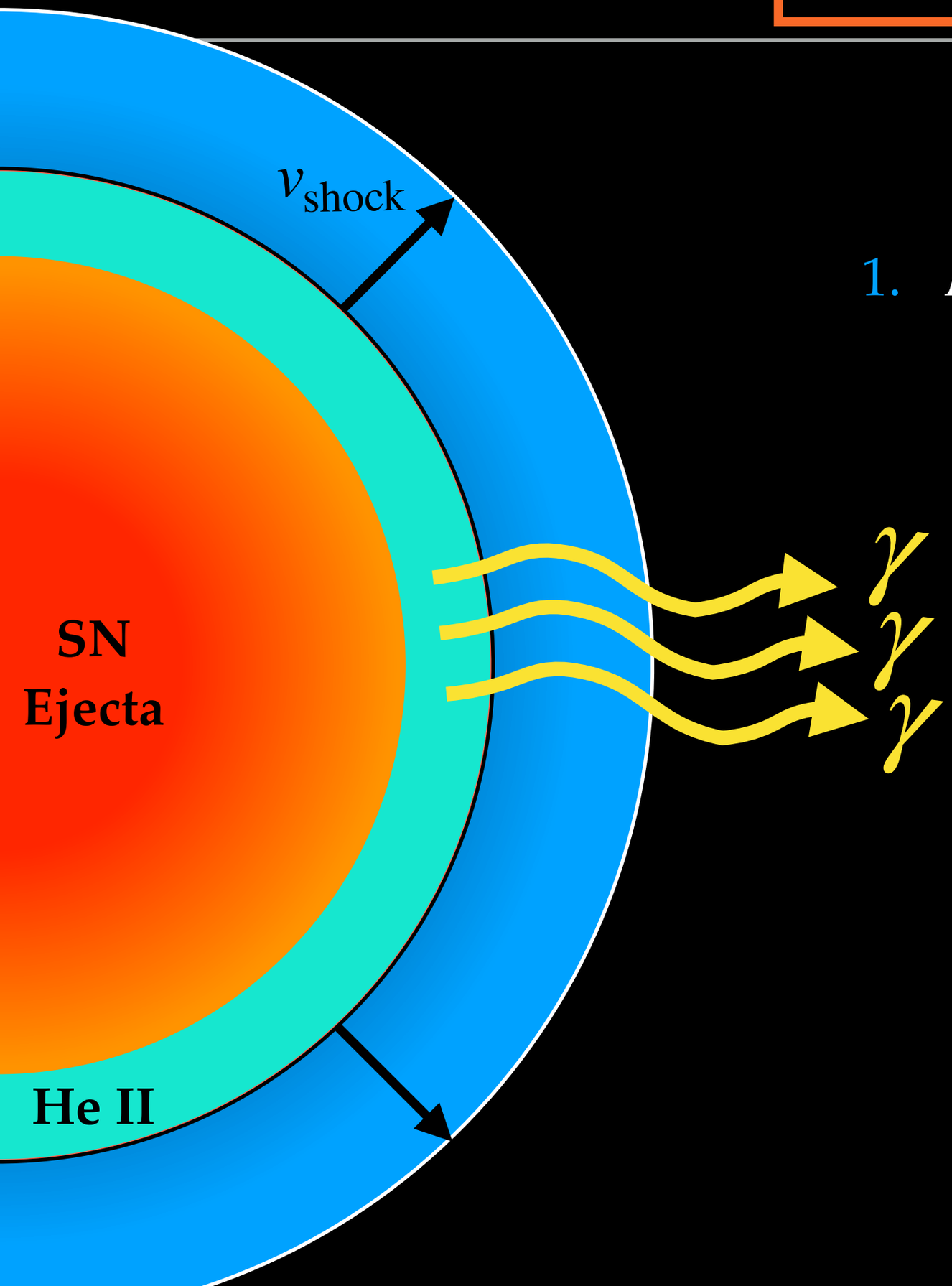


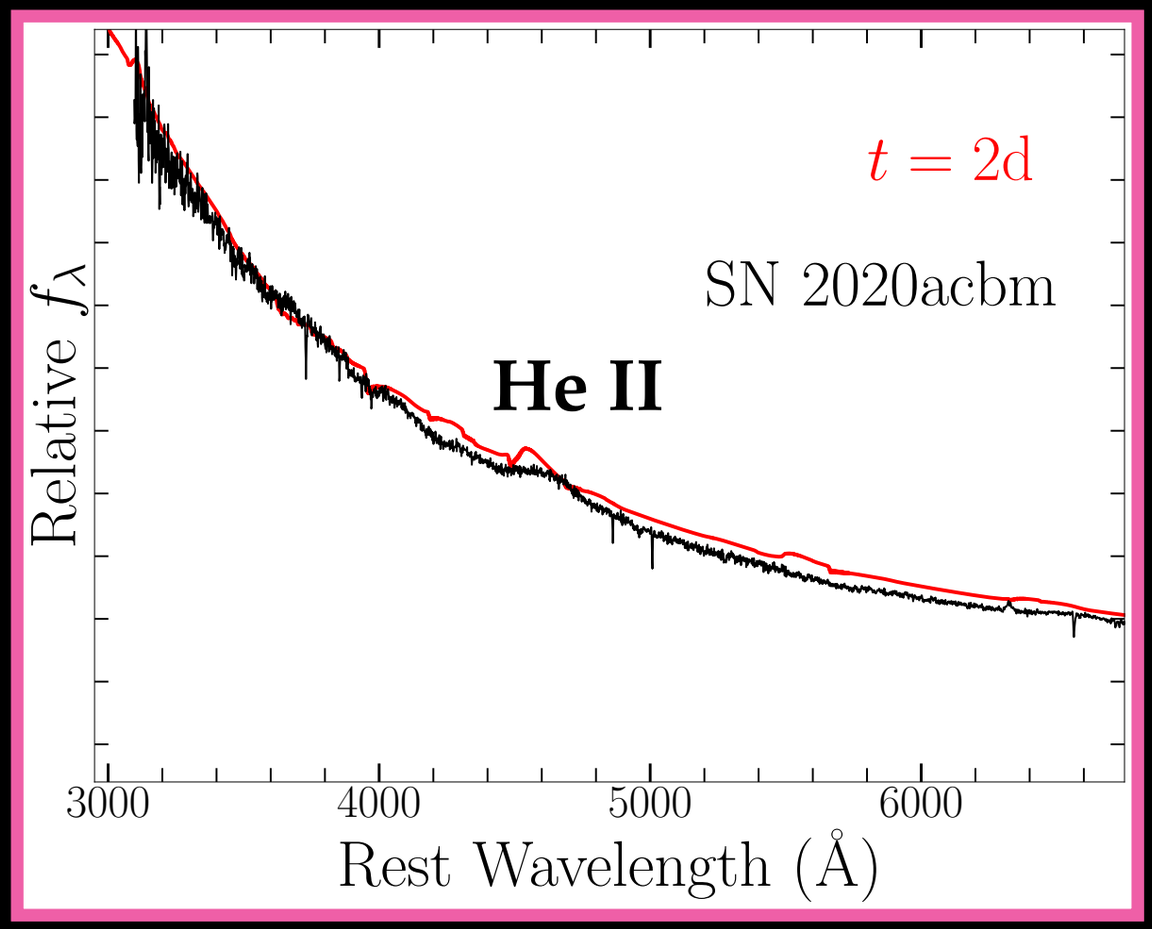
$t_{\rm lines} \approx t_{\rm rec}$

$t_{\rm IIn}$

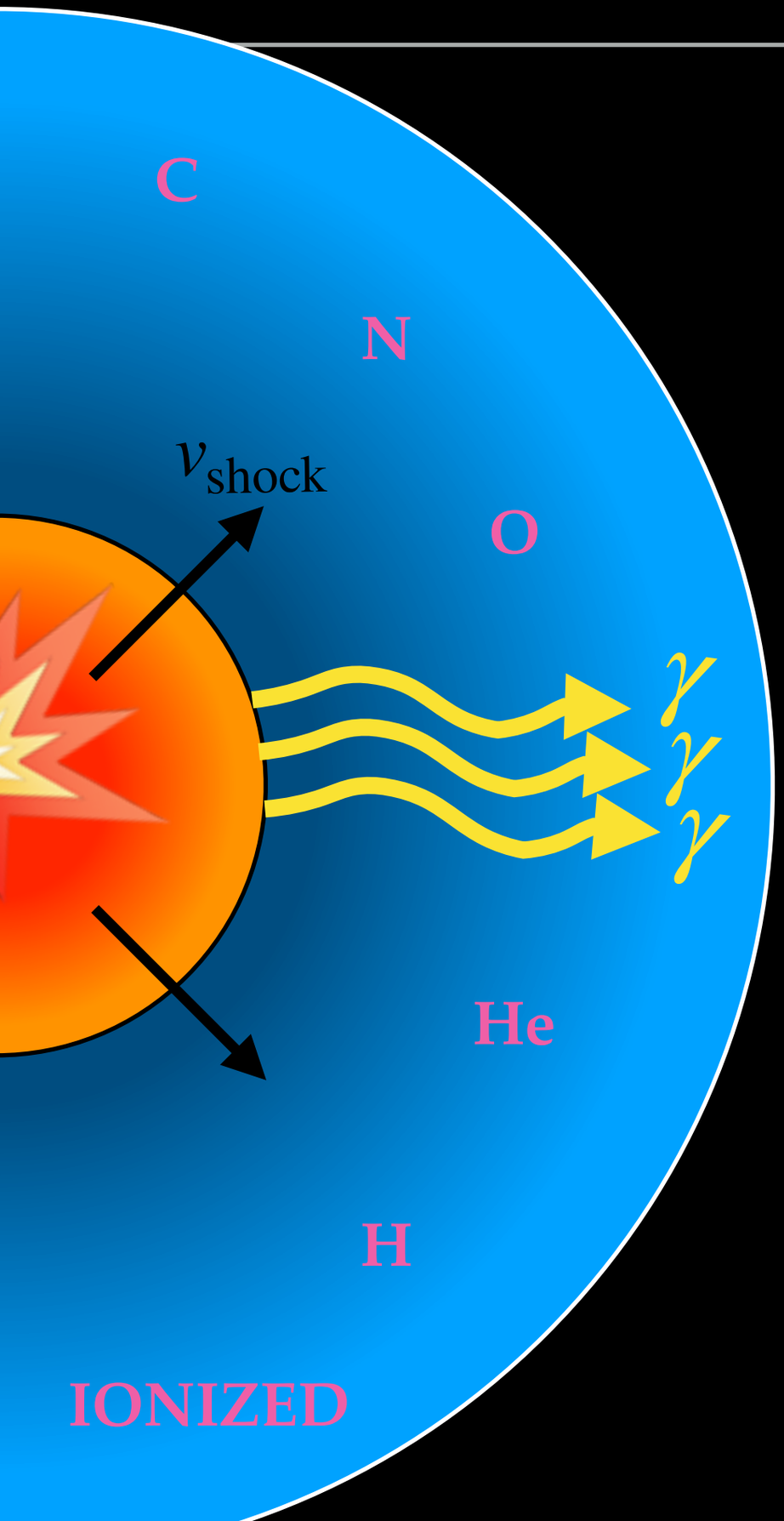


LIMITING CASES:

1. $\dot{M} = 10^{-6}\ \mathrm{M_\odot yr^{-1}}, r \approx 10^{15}$ cm

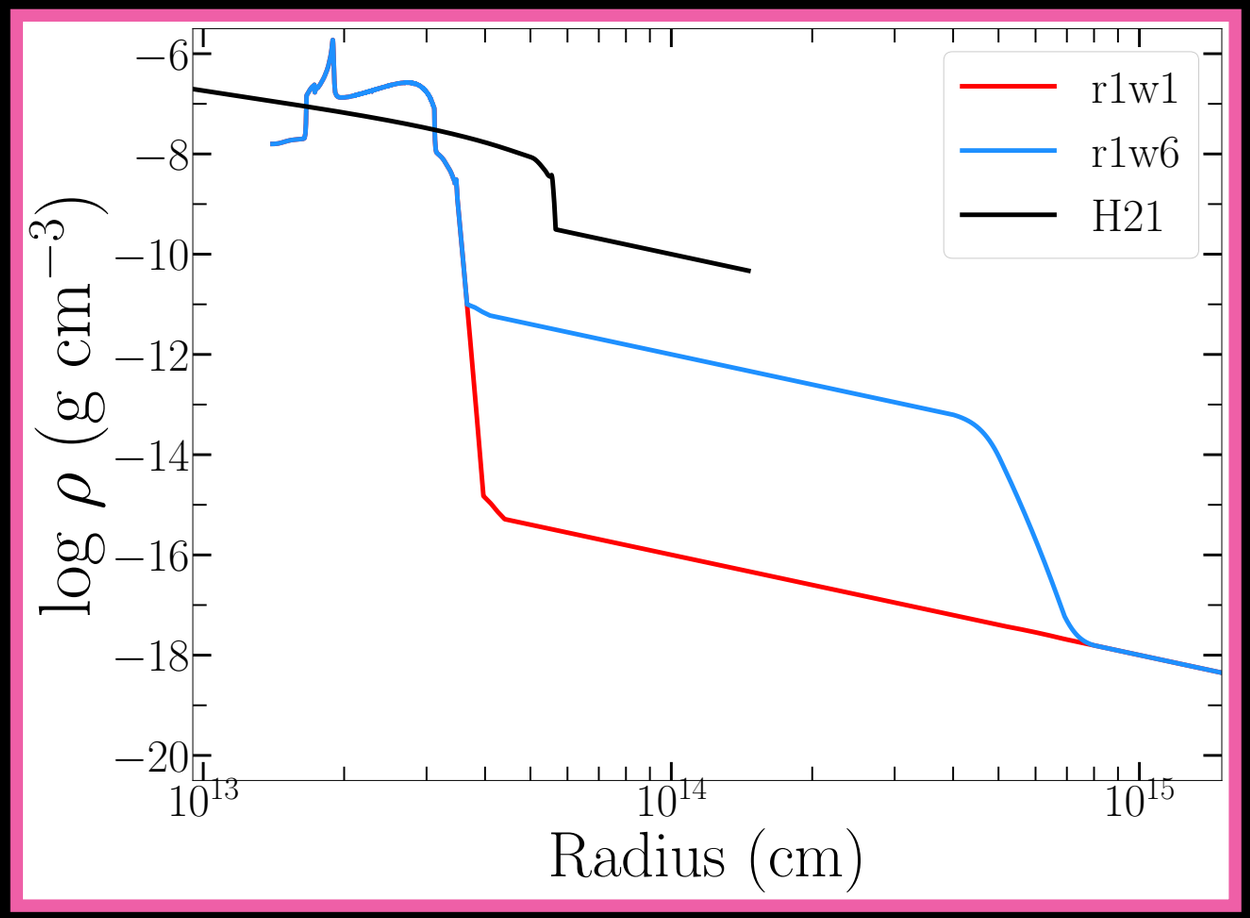


$t_{\rm II}$



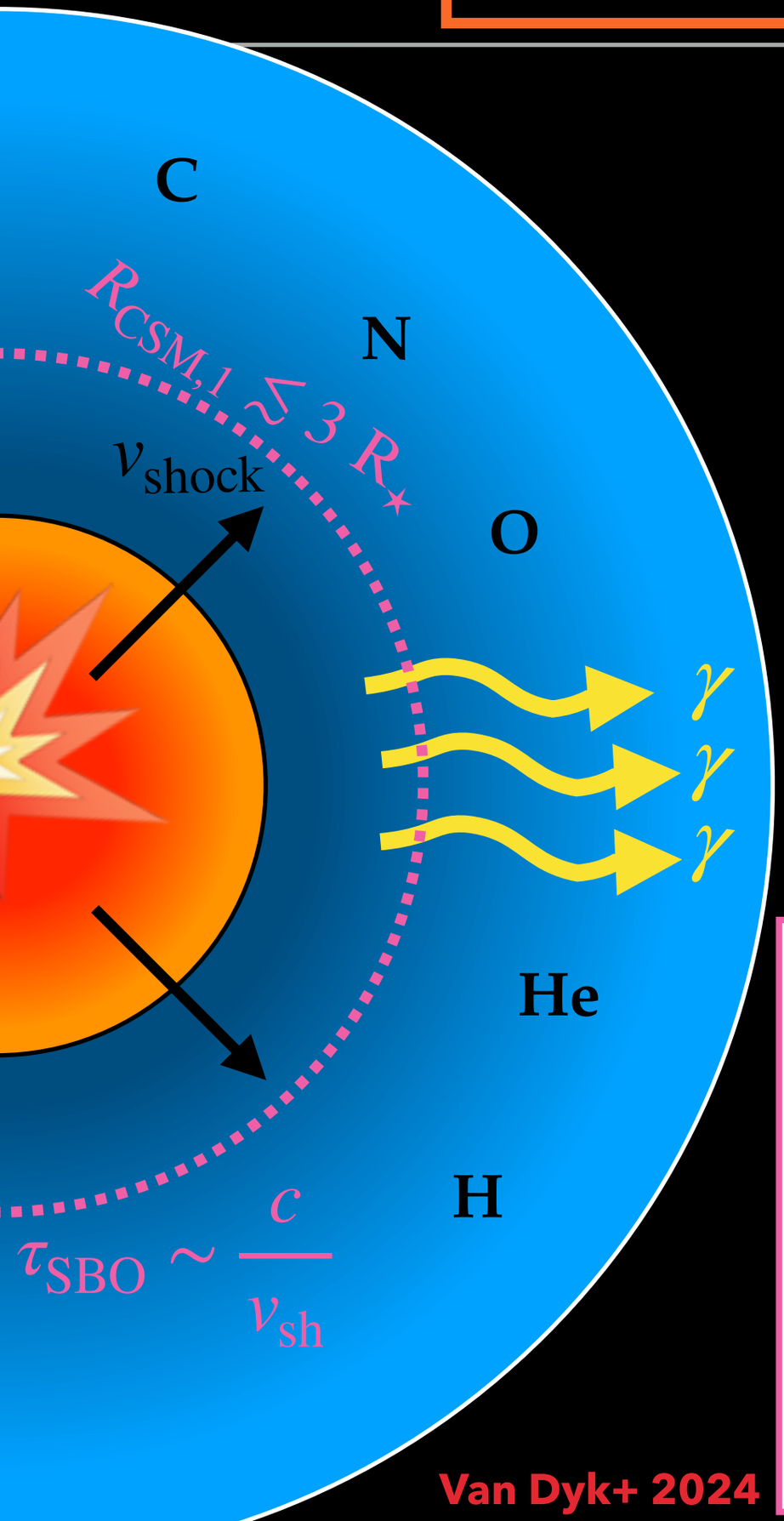
LIMITING CASES:

2. $\dot{M} = 10^{-2}\ \mathrm{M_\odot yr^{-1}}, r \approx 10^{15}$ cm



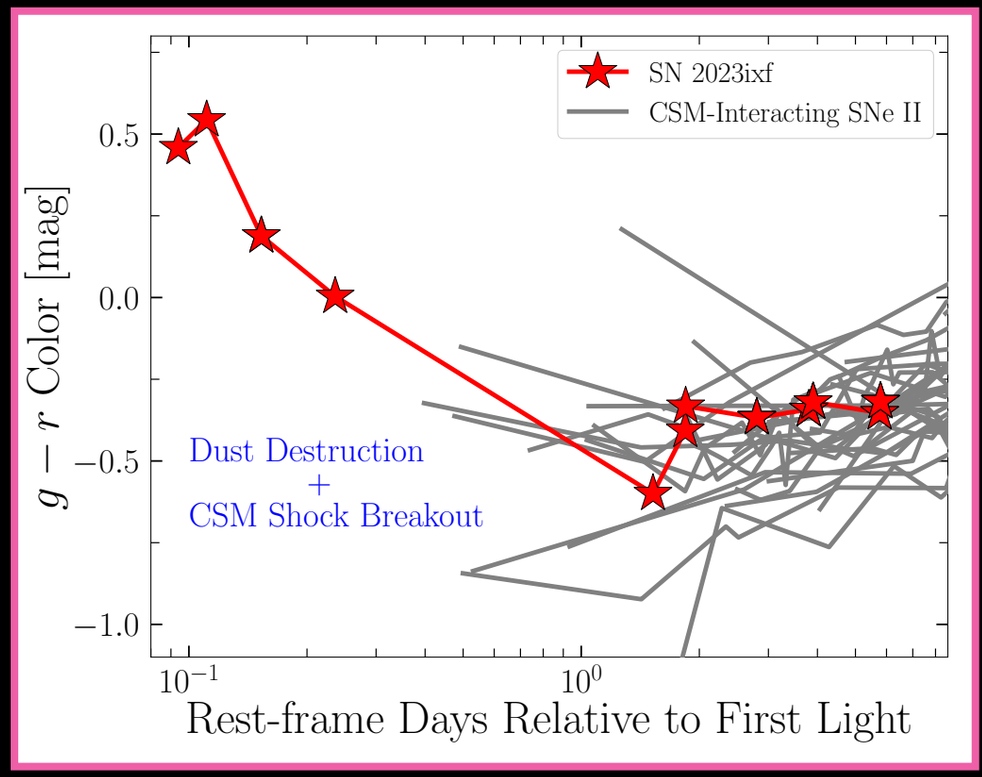
$t_{\rm flash}$

CSM SHOCK BREAKOUT

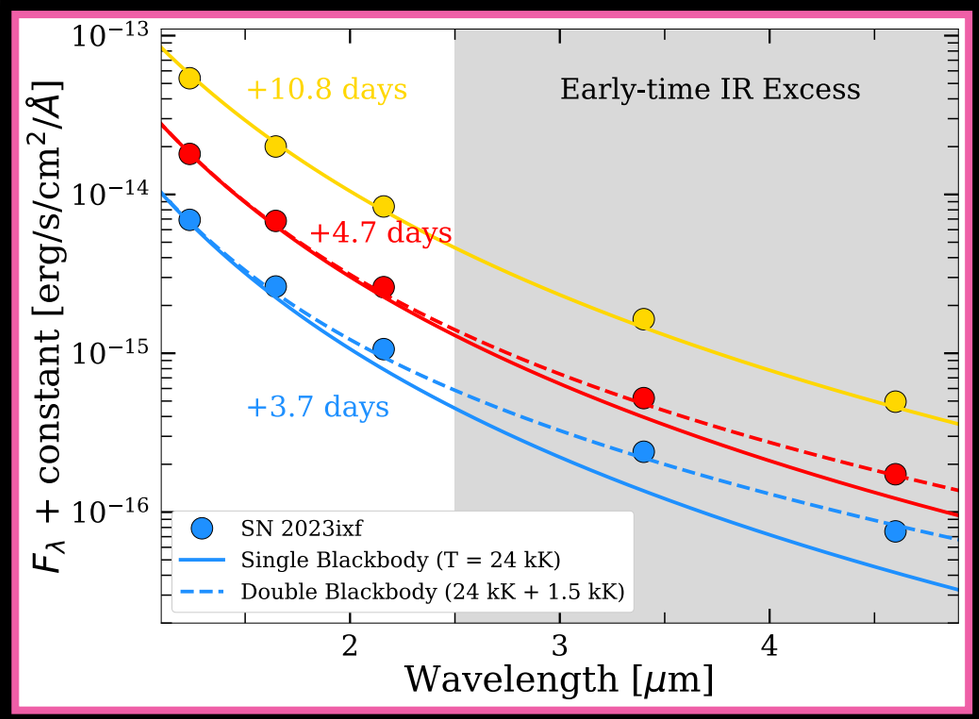


Van Dyk+ 2024

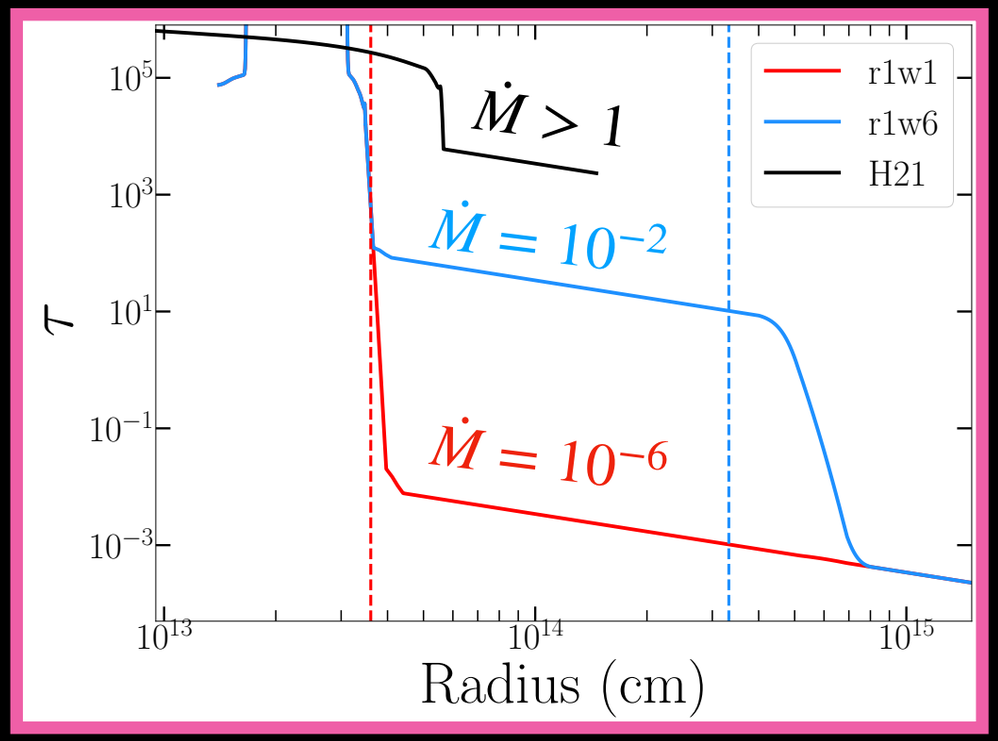
Dust destruction:

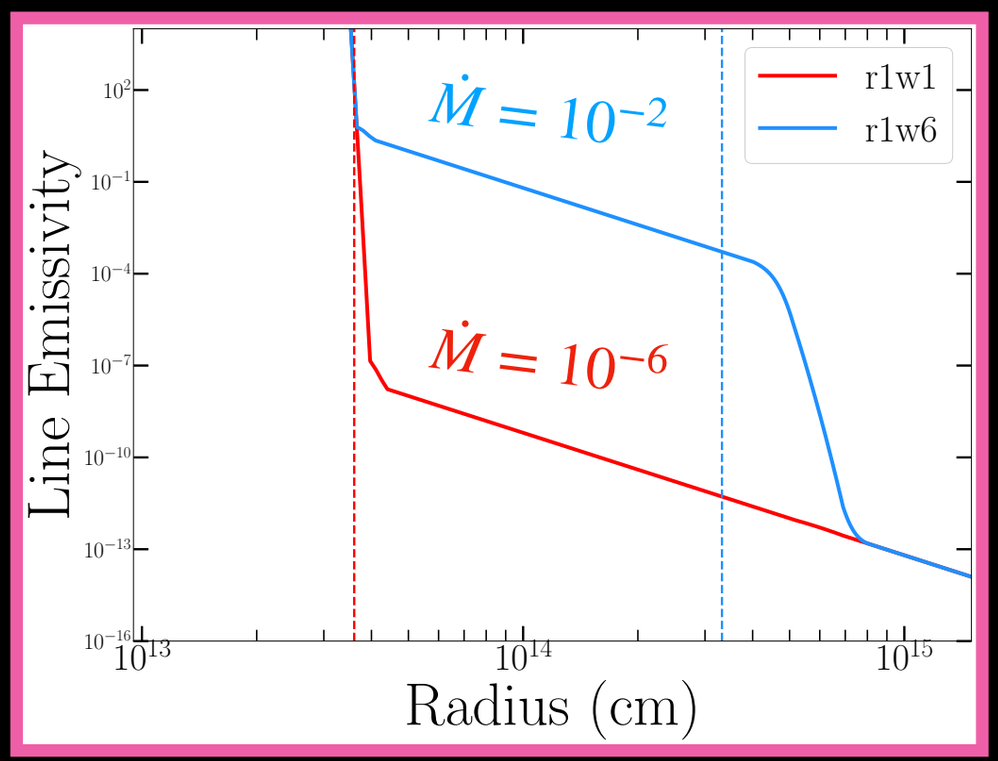


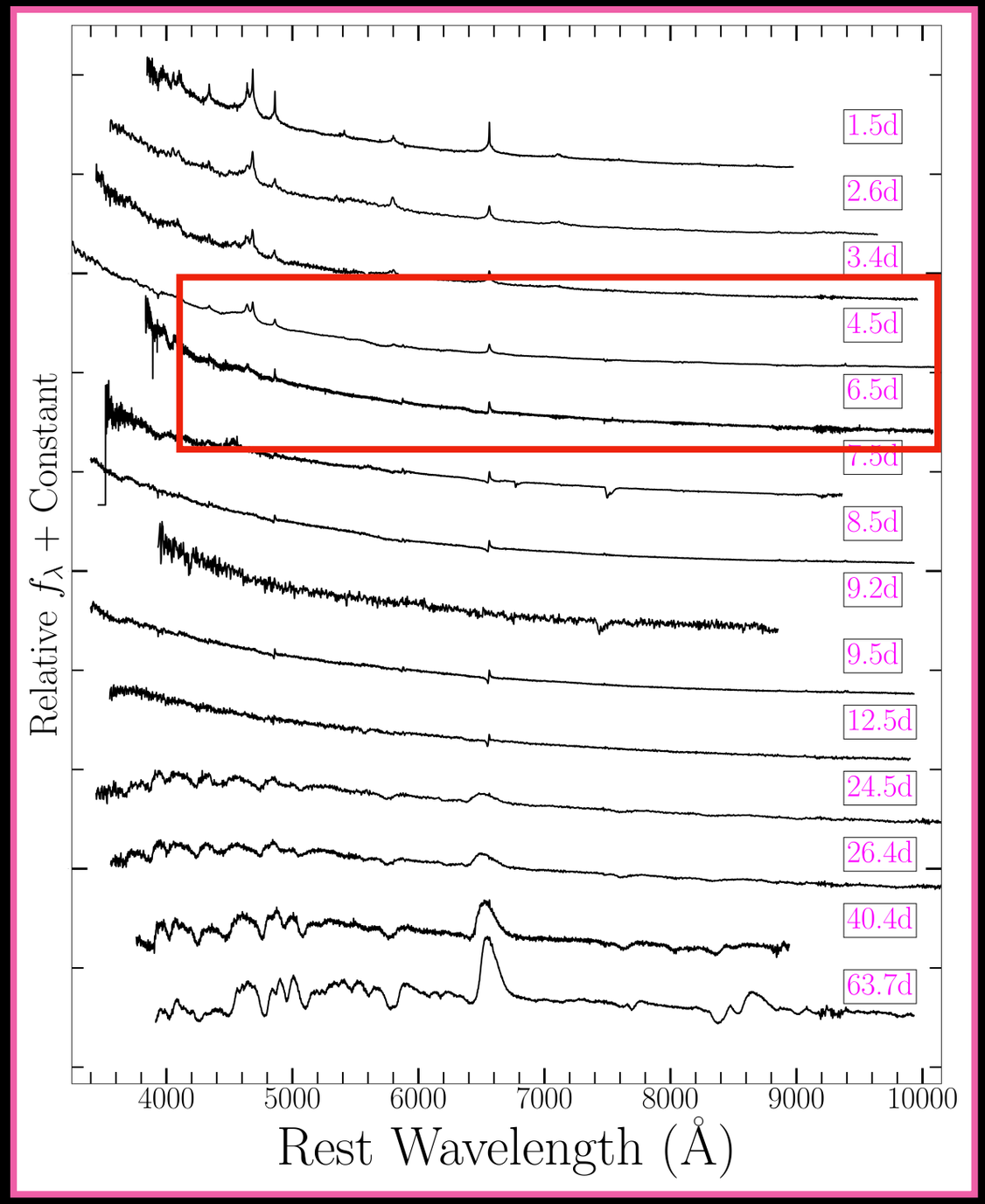
Li+ 2024



t_{SBO}







$t_{\mathrm{IIn}} = 5.5 \pm 1$ days

$\dot{M} \approx 10^{-3} - 10^{-2}\ \mathrm{M_\odot yr^{-1}}$

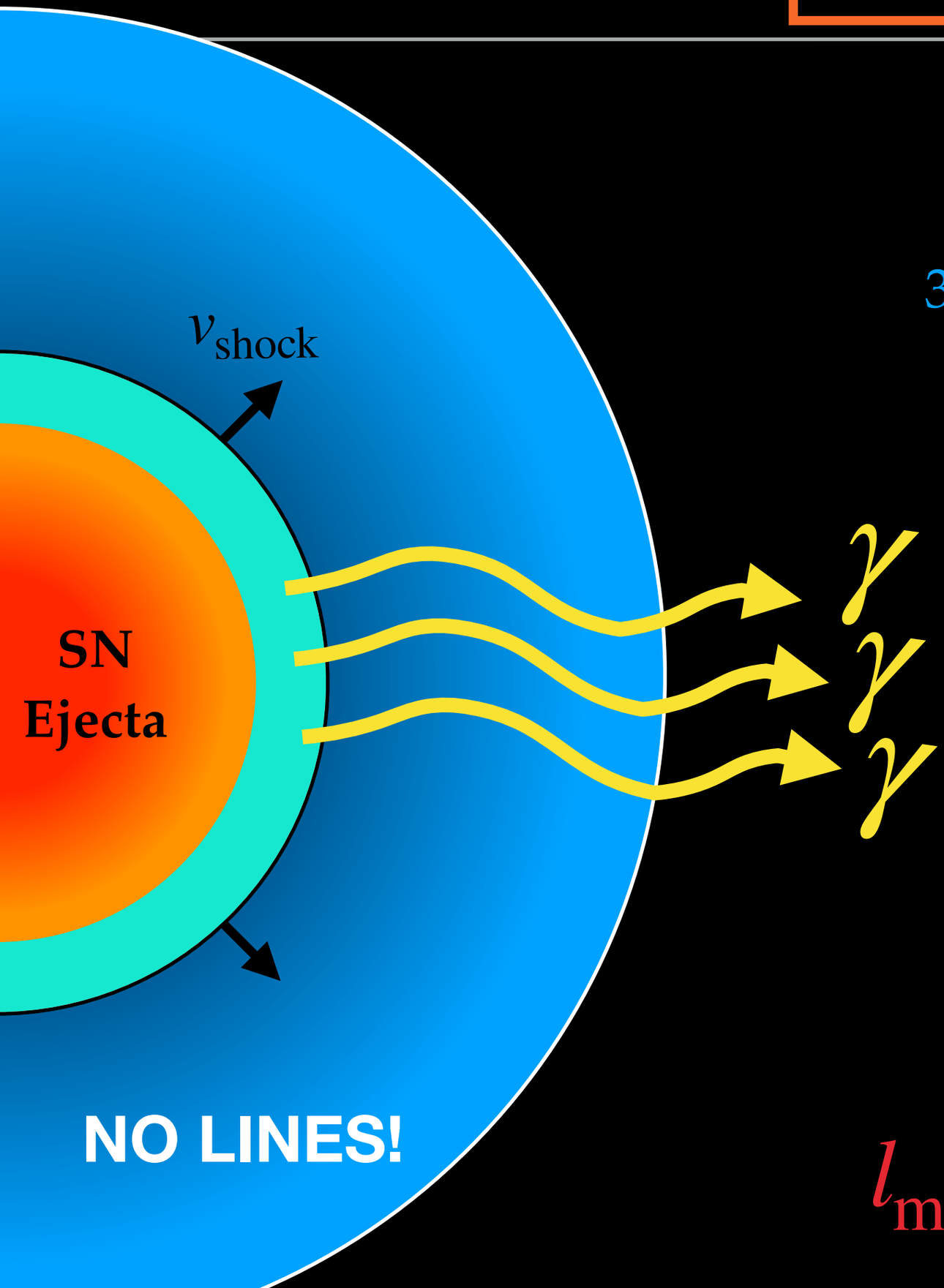
FUTURE: PRE-SN / SBO EMISSION

★ Rapid follow-up in the UV (*Swift*-UVOT Priority 0, *ULTRASAT, UVEX)* and X-rays (*Swift*-XRT, Einstein Probe, AXIS Probe)

★ Physically motivated precursor and SBO modeling

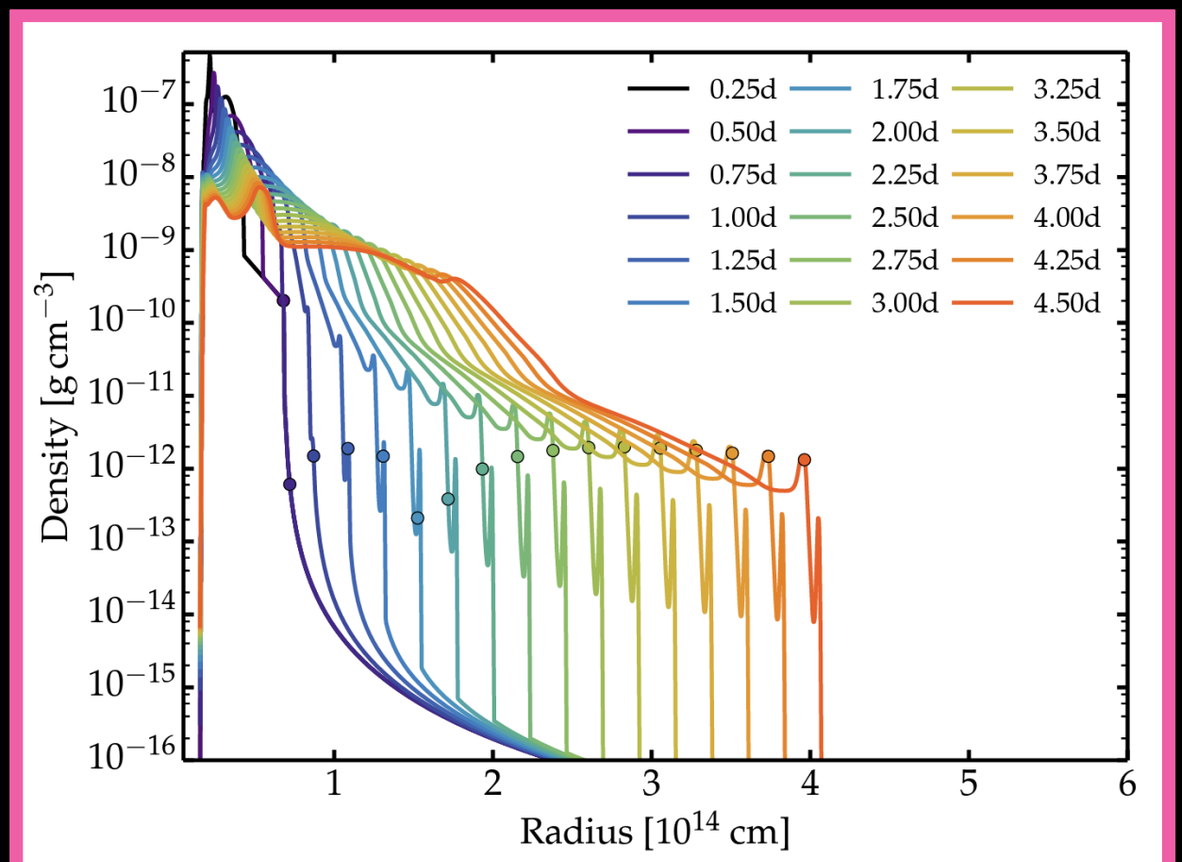
★ Larger datasets from survey telescopes (ZTF+LS4+LSST)

★ More pre-explosion imaging of nearby hosts with *JWST*/*HST*



LIMITING CASES:

3. $\dot{M} > 10^{-1}\ \mathrm{M_\odot yr^{-1}}, r < 10^{14}$ cm



(Dessart & Jacobson-Galan 2023)

$l_{\rm mfp} < r_{\rm CSM}$

$t_{\rm II}$